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REPLACEMENT SHELLS AROUND BATHOLITHS IN THE WASWANIPI DISTRICT NORTHWESTERN QUEBEC

B. C. FREEMAN
Ohio State University

ABSTRACT

The granitic masses of the western half of the Waswanipi map-area in northwestern Quebec are of two general types—(1) reddish to gray, coarse-grained, somewhat porphyritic, gneissic quartz-diorites, and (2) red to gray, medium- to fine-grained, quartz-diorites to granodiorites, and rarely soda granites. The rocks surrounding the batholiths are Keewatin-type volcanics, sediments, and anorthosite. Field evidence indicates that the gneiss is older than the massive quartz-diorite, and mineralogic and textural evidence indicates that the gneissic type represents a metamorphosed shell of invaded rocks altered by emanations from a solidifying batholith. The medium- to fine-grained type represents an intermediate zone between metamorphosed country rock-forming Type I and still later solidifying magma.

INTRODUCTION

The Waswanipi district of northwestern Quebec is one of the areas that has attracted prospectors in the last few years and for this reason has been geologically surveyed by Dominion and provincial surveys. The writer surveyed the western half of the Waswanipi map-area in 1936, under the general direction of G. W. H. Norman, for the Geological Survey of Canada. The northwestern quarter of the map-area with which this report deals lies between 49°30′ and 50° N. Lat. and 77° and 78° W. Long. The southern boundary is about eighty miles north of the village of Senneterre where the Canadian National Railway crosses the Bell River, and the northwest corner is about one hundred miles from James Bay.

The area lies within the clay belt formed by the deposition of clay in the basin of glacial Lake Ojibway. The surface therefore is monotonously flat, with muddy lakes and rivers. A few of the higher rock and boulder knolls remained above the level of deposition of lake clays and form the few low hills of the district.

The consolidated rock is all pre-Cambrian in age. The oldest series is a complex of Keewatin-type volcanic rocks and scattered belts of conglomerate and feldspathic schists, probably of the same general age as the volcanic complex. Intruding these rocks is a batholithic mass of basic rocks called the Bell River anorthosite, several masses of potash-poor rocks referred to as granites, and quite fresh diabase and lamprophyre dikes. The granite forms the bedrock over approximately half the area. The distribution of the rocks is shown in Figure 1.

VOLCANIC ROCKS

The Keewatin-type volcanic rocks are very similar to those in adjoining areas and consist of altered lavas and related rocks predominantly basic to intermediate in composition but including acid flows and tuffs.

The basic and intermediate flows were originally composed of plagioclase and pyroxene, but these primary constituents are almost completely altered—the former to mixtures of chlorite, carbonates, and iron oxides, and the latter to carbonates, in large part calcite, white mica, and epidote or zoisite. The more acid types have resisted alteration better, some plagioclase near albite still remaining in a mat of zoisite, quartz, white mica, carbonate, and chlorite. The alteration has been brought about without destroying the original textures and structures, that is, it has been a metasomatic change brought about by pervasive emanations. This type of alteration has been noted in other localities, notably in the district around Noranda.[1] A specimen of dacite[2] collected on the shore of MacIvor Lake shows marked evidence of hydrothermal replacement. The rock is light-gray, beautifully pillowed lava that appears macroscopically to be nearly as fresh as when it was formed. In thin sec-

[1] H. C. Cooke, W. F. James, and J. B. Mawdsley, "Geology and Ore Deposits of Rouyn-Harricanaw Region, Quebec," *Geol. Surv. Canada, Mem. 166* (1931), pp. 25–26.

[2] For the usage of dacite for such altered rocks see *ibid.*, p. 26.

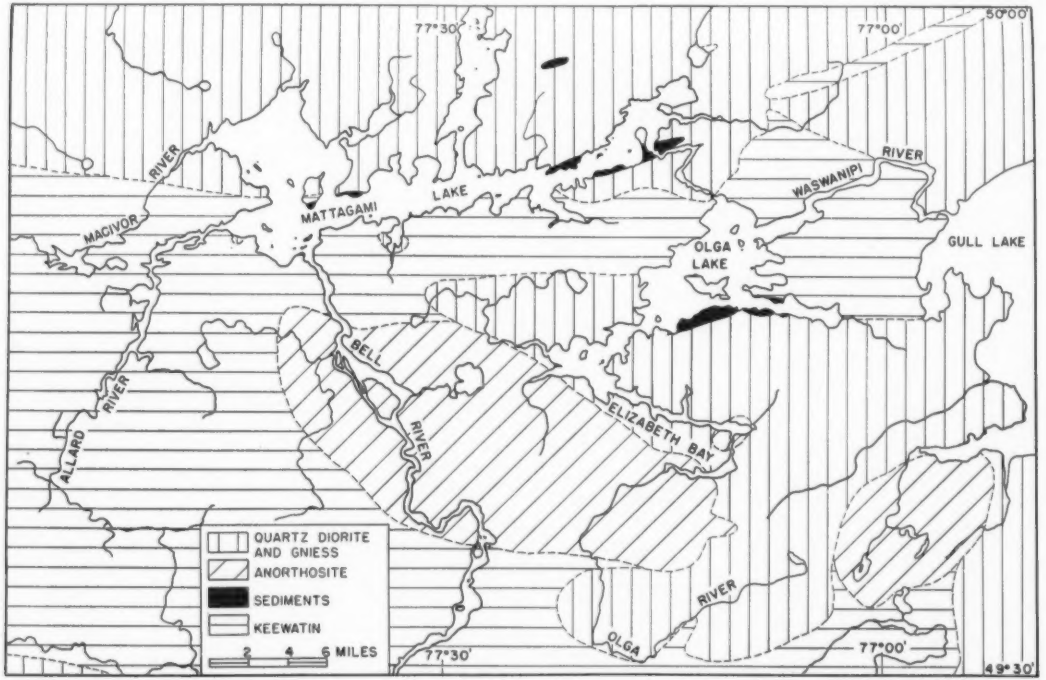

FIG. 1.—Map of the northwestern part of the Waswanipi District

tion, however, it is seen that porphyroblasts 1–2 mm. across, composed of aggregates of quartz, and grains of prehnite make up 10 per cent of the rock. The quartz is partly in sutured grains, partly in euhedral crystals. The base is composed of a felted mass of needles of zoisite or other epidote-like mineral, anhedral quartz grains, albite laths, and titanite. The approximate percentages are: zoisite, 40; quartz, 25; albite, 20; and titanite, 5. Tiny veinlets of quartz, some of them in optical continuity with the quartz of the porphyroblasts, and of calcite cut the other constituents. Probably everything except the albite and some of the quartz is secondary.

SEDIMENTS

The sedimentary rocks are present only in small amount and are very poorly exposed. Later intrusion and folding has modified the structure so much that the sedimentary-volcanic relationship cannot be determined with confidence. No marked unconformity is shown, but conformity can be neither proved nor disproved. The available evidence indicates that the sediments were deposited during the waning stages of the vulcanism responsible for the volcanic complex.

The sediments are largely quartz-biotite schists. Garnets are present in some places, notably on the south side of Olga Lake. A little hornblende is present and chlorite is fairly common. Feldspar is rare. The proportion of quartz and biotite varies, causing lighter and darker beds. The sediments apparently ranged from graywackes through impure sandstones. The Mattagami Lake band is characterized by cross-bedding and the presence of peculiar conglomerates with cobbles scattered very sparingly through the matrix. These conglomerates are similar in this respect to some in the Opemiska quadrangle.[3]

GABBRO-ANORTHOSITE

There are three masses of an altered basic intrusive which, though now separated from one another by later quartz-diorite, are doubtless parts of a single intrusive mass. The basic rock has been altered to such an extent that the original composition cannot be accurately

[3] Carl Tolman, "An Early Pre-Cambrian Sedimentary Series in Northern Quebec," *Jour. Geol.*, Vol. XL (1932), p. 360.

determined. A very small amount of the intrusive is a true anorthosite composed almost entirely of very basic plagioclase. In most places, however, the plagioclase is a mat of alteration products including white mica, zoisite, chlorite, calcite, and quartz, and forms only about half the rock, the rest being made up of various ferromagnesian constituents, principally hornblende, antigorite, and chlorite, with some augite and hypersthene. The pyroxenes are apparently primary, but the others are probably secondary.

GRANITIC ROCKS

There are two main areas of granite rocks. One stretches across the north side of the area and extends for long distances not only east and west but northward as well. The rock is prevailingly gray in color and gneissic in structure and will be referred to as the Mattagami gneiss. The other crosses Olga and Gull lakes and is markedly similar to other masses to the south. It is massive, reddish to gray-colored rock, and will be called the Olga quartz-diorite. Mattagami Lake therefore lies near the junction of two types of intrusive rocks. There has been some question about the relative ages of these rocks, but the north or Mattagami Lake type has generally been regarded as older than the Olga Lake type.[4]

MATTAGAMI GNEISS

General character.—The Mattagami Lake mass is composed principally of gray, gneissic rock cut by innumerable stringers and dikes of fine-grained, massive, gray to reddish-colored rock, and by pegmatites. It in turn has inclusions of schistose hornblendites, probably representing altered country rock. The gneiss is variable. The main type is a coarse gneiss with prominent, glistening black folia of biotite or hornblende, up to ½ inch long, in a slightly brownish-gray matrix composed of fractured augen of white oligoclase and transparent, somewhat smoky quartz, surrounded by saccharoidal quartz, biotite, hornblende, and oligoclase. The chief components of the rock are quartz, oligoclase, and biotite or hornblende in roughly equal amounts, though the proportions vary. In some places quartz

[4] A. H. Lang, "Waswanipi Lake Area, Quebec," *Geol. Surv. Canada Summ. Rep.* Part D (1932), p. 42.

is nearly lacking. The chief ferromagnesian mineral may be either biotite or hornblende. In most places the oligoclase is white or nearly so, but in other places it is quite red and altered. Very little potash feldspar is present, and is microcline rather than orthoclase.

The matrix surrounding the larger individuals is composed of xenomorphic-quartz grains, laths of greenish-brown biotite and blue-green hornblende with a few rounded oligoclase grains, some magnetite, and a little epidote. The matrix of the biotite gneiss in thin section is very strikingly similar to quartz-biotite schists that have resulted from the metamorphism of some of the Mattagami Lake sediments.

The larger individuals of quartz and oligoclase are fractured somewhat but not badly sheared. Some of the quartz grains show strain extinction, and all are crowded with dusty inclusions. Most of the oligoclase is fresh and well twinned, and some is zoned. A few grains are altered to a saussuritic mat over irregular areas. Complete alteration of this kind destroys the twinning and causes the red appearance of some of the feldspar. Biotite forms large flaky aggregates which wrap around the quartz and oligoclase augen and extend as stringers beyond them. Hornblende is partly in rude augen and partly in wedge-shaped masses with long, narrow tails. The arrangement of the ferromagnesian mineral serves to emphasize the gneissic character.

Massive apophyses.—The apophyses of massive gray to red rock that cut the gneiss are very irregular in shape and range in size from masses several hundred feet across to mere stringers. There are no chilled margins, and some of the contacts are gradational. In many places different phases meet abruptly along an irregular line but with no change in texture between the material at the contact and that within the mass.

There are several gray phases, differing only in amount of dark constituent and therefore in shade. The more mafic darker varieties are cut by lighter-gray apophyses. The gray phase is cut by the red phase. There is a series ranging from gneiss through numerous gray phases to a red phase, and any member may cut any older one, i.e., red apophyses cut gneiss in places as well as gray rock, and light-gray phases cut not only darker-gray phases but also gneiss.

Gray phases.—The gray phases are quartz-diorites, composed principally of oligoclase—roughly two-thirds—and quartz—about one-third—with variable amounts of biotite—but not over 10 per cent. Microcline, epidote, and apatite are prominent accessories. The oligoclase is in very ragged individuals which are altered in irregular patches and around the edges rather than in the center of grains. The alteration products are apparently a mixture of epidote, zoisite, and white mica. This is not true saussurite since there is no albite and the alteration products are larger than those produced by typical saussuritization. Phemister has described an alteration similar to the one occurring here.[5] He gives analyses of little-altered and altered plagioclase from the Cobalt diabase, which show a remarkable increase in potash content in the altered plagioclase, leading to the conclusion that the white mica is related to sericite.[6] Potash apparently had been introduced into the mineral during alteration, probably by a concentration of late magmatic liquid, i.e., water.

Albite twinning is present only as vestiges so that determinations based on extinction angles are a trifle uncertain. The mineral is optically positive, and the index agrees with that of a plagioclase with a composition of $Ab_{85}An_{15}$.

Quartz is present in slightly strained, sutured individuals that penetrate the oligoclase in replacement veinlets, and also is in smaller rounded grains between and within oligoclase individuals. Apparently it has replaced oligoclase on a large scale. Some of the quartz is broken into rude squares by tiny fractures due to the development of the rhombohedral parting.

Biotite is in ragged laths, partly chloritized, and with numerous black inclusions. Much of it is in ragged remnants wholly within plagioclase and has been either corroded or replaced by oligoclase.

Epidote and zoisite are in small grains (0.01 mm.) in altered oligoclase. Epidote also occurs in grains up to 1 mm. across (Fig. 2, *C*). These larger grains show replacement outlines against both oligoclase and biotite (Fig. 3, *B* and *E*).

[5] T. C. Phemister, "A Comparison of the Keweenawan Sill-Rocks of Sudbury and Cobalt, Ontario," *Trans. Roy. Soc. Canada*, Vol. XXII (1928), p. 148.

[6] *Ibid.*, pp. 149–50, 164–65.

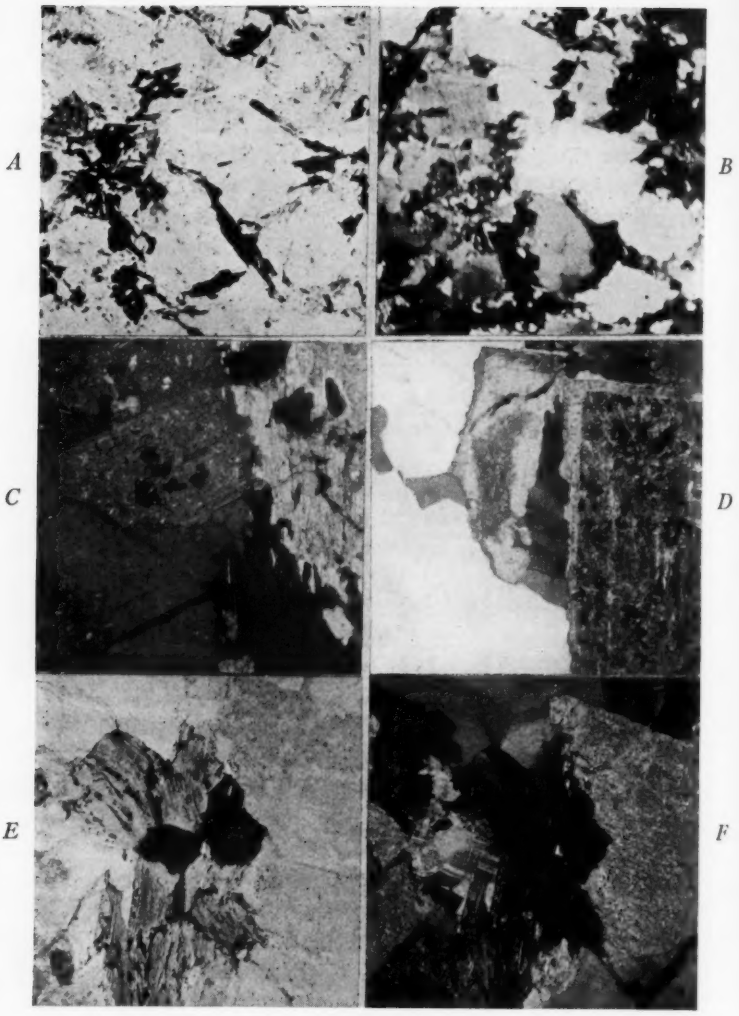

FIG. 2.—*A*, Ordinary light. Texture of quartz-diorite. ×24. *B*, Nicols crossed. Same field as *A*. ×21. *C*, Nicols crossed. Altered oligoclase with six epidote grains, black, all in same optical orientation. Oligoclase crystal, lower left, has a rim of clear albite. ×48. *D*, Nicols crossed. Oligoclase replaced by albite, dark gray in center of field. White and light gray is quartz. ×48. *E*, Ordinary light. Magnetite, black in chloritized biotite and dark gray in quartz and feldspar. ×54. *F*, Nicols crossed. Same field as *E*. The streak of magnetite and hematite dust in the quartz in the upper-right corner merges with the specks of iron dust in the oligoclase. ×48.

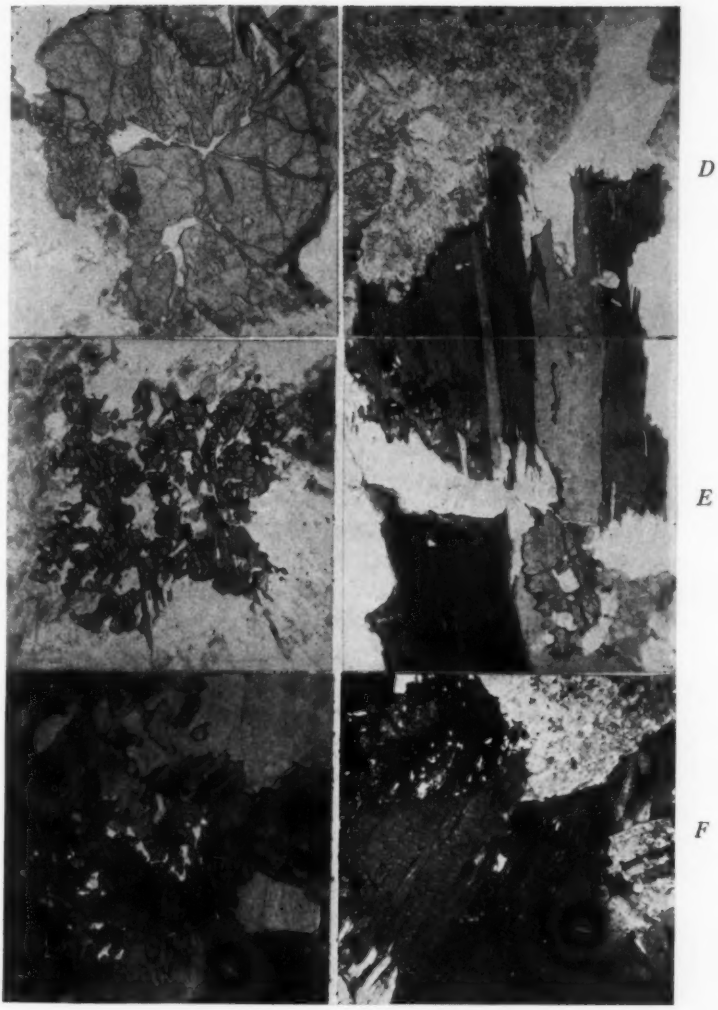

FIG. 3.—*A*, Ordinary light. Quartz replacing epidote and producing poikilitic texture. ×54. *B*, Ordinary light. Poikilitic epidote inundated by quartz, interpreted as having replaced the epidote. The two flakes of biotite in the epidote are in the same optical orientation. ×54. *C*, Nicols crossed. Same field as *B*. Microcline, medium gray, in upper right has replaced oligoclase, darker remnants in upper center. ×48. *D*, Ordinary light. Biotite and chlorite replaced by albite. ×54. *E*, Ordinary light. Biotite, chlorite, and epidote replaced by quartz. ×54. *F*, Nicols crossed. Same field as *D* and *E*. Albite, wavy extinction, replaces rest. Quartz, light gray, lower-left corner, replaces ferromagnesian minerals. ×48.

The paragenesis of the minerals is shown in Table 1. The place of the alteration of the oligoclase and the chloritization of the biotite in the sequence shown in Table 1 is uncertain. The alteration of plagioclase to epidote and white mica is possibly related to the development of the large grains of epidote. Epidotization and sericitization are types of alteration in contact metamorphism. Lovering has recently described such a mineral deposit in which the formation of sericite, chlorite, and epidote was essentially simultaneous.[7] Ross regards epidote and zoisite as hypothermal minerals in the south-

TABLE 1

Quartz (small rounded grains)	———
Biotite	———
Oligoclase	———
Epidote	———
Quartz (large individuals)	———

ern Appalachians.[8] He places chlorite in the hypothermal stage but later than epidote.[9] These considerations point to the close association of these minerals and in the paragenetic sketch shown in Table 1 plagioclase alteration to epidote and white mica and biotite alteration to chlorite should probably be placed in the epidote stage.

The place of apatite depends upon the interpretation of euhedral crystals enclosed in other minerals. Most petrographers regard these as earlier than the enclosing minerals, but many investigators regard them as later replacements.[10] If apatite is due to replacement, it fits into the scheme between epidote and quartz since it is very slightly corroded by quartz and occurs in sharply bounded crystals in the other minerals. If it was not formed by replacement, it is the oldest mineral in the suite. The early quartz and the biotite are probably remnants of an original rock altered by a series of replacements.

Red phase.—The reddish apophyses are leuco-granodiorites, aplitic in appearance and fine grained ($\frac{1}{2}$ mm.). They are composed of

[7] T. S. Lovering, "Geology and Ore Deposits of the Montezuma Quadrangle, Colorado," *U.S. Geol. Surv. Prof. Paper 178* (1935), pp. 42–45.

[8] Clarence S. Ross, "Origin of the Copper Deposits of the Ducktown Type in the Southern Appalachian Region," *U.S. Geol. Surv. Prof. Paper 179* (1935), p. 28.

[9] *Ibid.*, pp. 31–32.

[10] For a detailed discussion see *ibid.*, p. 9.

oligoclase-albite, quartz, and microcline, with a little mica, a very small amount of epidote, and a few cubes of pyrite. The minerals are in a confused mass of xenomorphic, irregular, embayed, ragged individuals, and the texture does not resemble any true igneous texture.

The plagioclase is largely altered to epidote and white mica—similar to the alteration in the gray apophyses—and contains quartz in small rounded grains with frayed edges and a few hexagonal crystals. Microcline is in irregular grains, meeting quartz with mu-

TABLE 2

Quartz	———		
Mica	———		
Oligoclase-albite	———		
Microcline	———	———	
Quartz	———	———	

tual boundaries and embaying plagioclase. Quartz is present in small rounded grains and euhedral crystals as stated above, and also in larger, irregular grains, many of which show a rhombohedral parting. The larger grains have replaced plagioclase and mica. There are thus two generations of quartz. The micas are in small ragged remnants composed of a parallel intergrowth of a green biotite and colorless mica—either bleached biotite or muscovite. Some of it is chloritized. The early quartz and the mica seem to be remnants of original rock engulfed in the later minerals.

The paragenesis of this type is shown in Table 2. The sequence in this phase is similar to that in the gray type. The differences are the more sodic character of the plagioclase and the presence of microcline.

Pegmatites and vein quartz.—Small pegmatites, up to a foot or so in width, composed of quartz and microcline in grains about an inch across, are abundant and cut all the other rocks. Quartz veinlets from an inch in width down to mere films are very numerous.

OLGA QUARTZ-DIORITE

The quartz-diorite around Olga and Gull lakes is a somewhat variable rock of medium texture, with grains about 2–3 mm. in

size, though there are occasional plagioclase individuals up to 5 mm. The texture is hypautomorphic granular but differs from the usual hypautomorphic texture in that the plagioclase individuals, making up about two-thirds of the rock, are nearly automorphic and are separated by a xenomorphic base, principally quartz but with variable amounts of biotite and/or hornblende. If there were a more distinct difference of grain size between the feldspar crystals and the rest, the texture would be porphyritic. There is some resemblance to ophitic texture in which plagioclase laths are involved in

TABLE 3

MODE OF THE OLGA QUARTZ-DIORITE

Mineral	Per Cent	Per Cent
Oligoclase	65	55–84
Quartz	25	10–45
Biotite	10	0–10
Hornblende		0–10
Epidote		tr–5
Apatite, Magnetite, Titanite, Pyrite	Accessory	Accessory
Microcline, Albite	Variable; small amounts	0–30; 0–6

a base of xenomorphic augite The rock does not look at all like a diabase; therefore the term "ophitic" is inapplicable. The greater part of the rock is gray in color, but there are innumerable areas of various sizes and shapes that are red, due to the alteration of the oligoclase (cf. Fig. 2, *A* and *B*).

The composition is variable. In Table 3 the approximate mode of most of the rock is given in the first column and the limits of each constituent found in the second column. The wide variations shown in the second column are due to alterations and replacements and represent variants occurring near the contacts and in small apophyses in country rock. These variants were obviously granitic and differ from the hybrid rock occurring in xenoliths.

Minerals of the normal quartz-diorite.—The normal quartz-diorite is an oligoclase-quartz-biotite rock with small amounts of microcline, hornblende, epidote, apatite, magnetite, and titanite. The

plagioclase is a median oligoclase, about $Ab_{80}An_{20}$, generally altered so that the twinning is partly or wholly obscured. The alteration is similar to that described above in the apophyses in the Mattagami gneiss, except that there is a large amount of opaque, reddish dust, probably hematite. The red-colored type owes its color to a very pronounced accumulation of the red specks. Some of the oligoclase is slightly zoned, and many of the grains are bounded by an outer rim of clear albite which meets the altered oligoclase core along a very irregular contact (Fig. 2, *C*). Albite also occurs in a few places as clear, untwinned, fresh-looking material that embays oligoclase in caries texture and penetrates it in tiny, irregular veinlets. The evidence of replacement of oligoclase by this type of albite is quite clear (Fig. 2, *D*).

Microline is present in small irregular grains which replace oligoclase and hornblende (Fig. 2, *F*). It is more abundant and widespread than albite but rarely forms more than 1–2 per cent of the rock.

Quartz occurs in two ways—in small blebs and in larger grains. Most of the larger grains are unchecked, unstrained, and are like ordinary interstitial quartz, but some show a pronounced development of rhombohedral parting. This type with the parting quite clearly replaces oligoclase and the ferromagnesian minerals. The quartz in the tiny blebs forms chadacrysts in hornblende, epidote, and biotite. Both hornblende and epidote are markedly poikilitic. Figure 3, *A* shows poikilitic epidote being replaced by quartz. The quartz chadacrysts are related to the replacement veinlets, and this suggests that the blebs are replacement bodies with the poikilitic ferromagnesian mineral acting as host to the quartz. Much of the quartz, probably over half of it, is in the usual grains interstitial to oligoclase and apparently represents material that crystallized from a magma. The rest is regarded as secondary, brought in by hydrothermal solutions and replacing the earlier constituents. There are very few bubbles in any of the quartz, but inclusions of black and red dust, probably iron oxide, are very numerous. The dust is arranged in lines along and near fractures. There are also many small, angular flakes resembling the white mica and zoisite of saussurite.

Biotite is the commonest ferromagnesian mineral. It is mostly yellow-brown in color, partly chloritized, and in ragged poikilitic flakes. Grains of iron ore and titanite are scattered through it (Figs. 3, *D* and *E*, and 2, *E* and *F*).

The hornblende is blue-green and may contain considerable soda, which would account for the blue shade. It is in smaller grains than biotite, is usually much less in amount, and is very markedly poikilitic.

Epidote occurs not only as small grains in plagioclase but also in aggregates of much larger grains associated with biotite and hornblende. All three ferromagnesian minerals—epidote, biotite, and hornblende—occur together, are poikilitic, and are replaced in part by quartz and microcline (Fig. 3, *B*). Epidote is so riddled by quartz that relationships to the other ferromagnesian minerals are uncertain. Relationships of the ferromagnesian minerals to oligoclase are also obscured by the presence of quartz between them and oligoclase. There is some evidence that epidote does replace biotite. In one slide biotite fragments in optical continuity are separated by an epidote grain. Both the epidote and the biotite are embayed in a very irregular manner by quartz, interpreted as replacing the ferromagnesian minerals. Biotite and hornblende probably belong to the magmatic stage and have crystallized later than the oligoclase. Epidote is probably later and may be hydrothermal.

Magnetite is an accessory and occurs in somewhat irregular grains, not in euhedral crystals. These grains lie along the boundaries of minerals and near fractures along which specks of iron dust are abundant. Its occurrence is somewhat similar to that of opaque oxides in anorthosites as described by Newhouse, who interprets them as later than feldspar and of the same age as the minerals between the feldspar grains.[11] By such an interpretation magnetite here would be placed with hornblende, biotite, and quartz. The grains are few in number, and the relationships between them and replacement quartz do not yield conclusive evidence of their relative ages. Where magnetite grains are most abundant the black specks of iron ore in the quartz are also most numerous and in places

[11] W. H. Newhouse, "Opaque Oxides and Sulphides in Common Igneous Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 22.

form irregular clots or nodes at the intersection of fractures (Figs. 2, *E* and *F*). This suggests that magnetite is a late mineral formed with or later than the replacement quartz. It may be of two ages, some early and some late. It is interpreted as a late mineral formed during the hydrothermal stage.

Titanite is present only in a few grains, and these are similar in shape to the magnetite grains but smaller. It is associated with magnetite and was probably formed at the same time.

TABLE 4

PARAGENESIS OF THE MINERALS OF THE OLGA QUARTZ-DIORITE

Mineral	Magmatic Stage	Hydrothermal Stage
Oligoclase	———	.....
Biotite	———	.....
Hornblende	———	.....
Quartz	———	———
Epidote	.....	———
Oligoclase alteration	.....	———
Albite	.....	———
Microcline	.....	———
Magnetite	— ? —	———
Titanite	— ? —	———
Apatite	— ? —	———

Apatite is present in euhedral, or nearly euhedral, crystals, occurring with the other minerals interstitial to feldspar. It is therefore later than feldspar, but whether it is regarded as having been formed with the biotite and hornblende or as a late replacement rests upon the interpretation placed upon euhedral boundaries. It may be a replacement that has taken its own crystal form. Apatite does occur in such forms in the metamorphic pyroxenites or apatite veins of Ontario and Quebec.

The paragenesis of the rock is believed to be as shown in Table 4.

CONTACT ROCKS

A wide band of altered rock forms a contract zone between the quartz-diorite and the country rocks. Owing to the scarcity of outcrops, the actual contact is exposed in only a few places but where exposed there is a wide zone of hybrid rock containing a multitude of ragged, dikelike apophyses. Where these masses of quartz-diorite

made up more than half the outcrop, it was mapped as quartz-diorite.

The apophyses are irregular in shape and lack chilled margins. The grain size in all of them, even streaks a quarter-inch wide, is about the same (2–3 mm.). The contacts are similar to those of replacement veins with ragged, oriented fragments of wall rock isolated within the apophyses. The evidence points toward the introduction of the quartz-diorite by tenuous solutions which replaced the wall rock, rather than to intrusion of a magma from which the constituents crystallized.

The country rock is of three general types—sediments, greenstones, and the Bell River anorthosite. In the sediments the process apparently occurred in three stages. First, oligoclase and quartz-porphyroblasts were developed in the quartz-biotite schist. Second, oligoclase and quartz replaced the schist so thoroughly along lines of easy access of solutions that a quartz-diorite dikelet was formed. Third, microcline, albite, and quartz replaced the earlier-formed oligoclase of the veinlets. The evidence for this conclusion lies in paragenetic studies similar to those described in detail for the sequence in the apophyses in the Mattagami gneiss.

In the greenstones the mass of alteration products was recrystallized near the contact to hornblendite or to a xenomorphic mass containing oligoclase and quartz in addition to the hornblende. This material was replaced by oligoclase, quartz, microcline, and albite to form hornblende-bearing quartz-diorite apophyses.

The anorthosite was altered somewhat differently. The plagioclase of the anorthosite is a basic andesine, everywhere more or less altered and it is accompanied by hornblende in fresh, glistening greenish-black needles and in aggregates of acicular crystals, in places forming three-fourths of the rock. Most, if not all, of this hornblende has been added to the anorthosite, though some of it may be the result of recrystallization of a primary pyroxene. Quartz-diorite replacement dikes cut this altered rock.

COMPARISON OF CONTACT ROCKS AND MATTAGAMI GNEISS

The Mattagami gneiss contains several rock types, all of which can be duplicated in specimens from the contact zones of the Olga

quartz-diorite. There are masses of sediments and greenstone within the gneissic area and paralleling the trend of the structure in the larger masses to the south. Hornblendic masses entirely similar to the recrystallized greenstone of the contacts are very numerous. Oligoclase and quartz-porphyroblasts are present in varying amounts, and when they make up about two-thirds of the mass, the result is the characteristic gneiss. Apophyses replace the gneiss in the same manner in which similar apophyses replace the contact rocks about the quartz-diorite.

The conclusion drawn from these facts is that the gneiss is a migmatite formed by recrystallization and metasomatic replacement of a shell above a crystallizing quartz-diorite magma. The migmatization is believed to have been caused by hydrothermal solutions. Hydrothermal solutions are derived from a magma and grade into the parent-substance. The distinction between the two has been aptly pointed out by Phemister.[12] A magma is a molten solution, fluid mainly through heat, and a hydrothermal solution owes its fluidity to the presence, in marked degree, of aqueous constituents. The elements of a magma obviously are unable to enter into the minute openings by which a replacing solution floods a rock; therefore widespread replacement is caused by hydrothermal solutions and not by magmas. This applies to the replacements that produced the hybrid rocks in which porphyroblasts are very prominent, to the introduction of hornblende into the anorthosite, and to the emplacement of the multitude of apophyses of quartz-diorite. It also applies to the alterations—the addition of microcline, quartz, and albite, and the formation of the epidote—in the quartz-diorite.

Hydrothermal replacement is recognized as a factor in the production of some igneous-type rocks. Bastin has shown that the dike-like aplites associated with the Nipissing diabase are not true dikes but were formed by hydrothermal replacement.[13] Goodspeed has recently described an occurrence of granodiorite which has resulted

[12] "Igneous Rocks of Sudbury and Their Relation to the Ore Deposits," *Ann. Rept. Ont. Bur. Mines*, Vol. XXXIV, Part VIII (1925), p. 52.

[13] E. S. Bastin, " 'Aplites' of Hydrothermal Origin Associated with Canadian Silver-Cobalt Ores," *Econ. Geol.*, Vol. XXX (1935), pp. 715–34.

from the metasomatism of hornfels.[14] The change of a quartz-diorite into an albite granite is described in detail by Gilluly.[15]

The importance of replacement in the formation of gneissic zones about some Colorado batholiths has been shown by Stark.[16] He considers the sequence of events to have been somewhat as follows.[17] Batholiths were intruded into rocks lying deep below the surface and notably heated in advance of the actual intrusion. These superheated rocks were penetrated by emanations from the batholith and changed into migmatites. The migmatized schists were intruded by viscous magmas that crystallized as stocks, lit-par-lit stringers, sills and dikes of pegmatite. These processes continued, and large masses of schist were replaced metasomatically.

Billings has made an intensive study of zoning in an area of regionally metamorphosed rocks and has shown that the intensity of metamorphism increases toward batholiths intruded during the metamorphism. He believes that the cause of this increased intensity was heat and solutions from the intrusives.[18] Barth has described an area in which he believes magmatic solutions played a very important part in the metamorphism.[19] He states:

> The pelitic sediments of the present area have been permeated by solutions responsible for the regional metamorphism of the sediments. It seems reasonable to look upon these solutions as derivatives of the magmatic rocks, which were simultaneously intruded into the sediments.[20]

Anderson has concluded that the Cassia batholith in Idaho was notably enlarged by the conversion of enormous quantities of wall

[14] G. E. Goodspeed, "Small Granodiorite Blocks Formed by Additive Metamorphism," *Jour. Geol.*, Vol. XLV (1937), pp. 741–62.

[15] James Gilluly, "Replacement Origin of the Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Prof. Paper 175C* (1933), pp. 65–81.

[16] J. T. Stark, "Migmatites of the Sawatch Range, Colorado," *Jour. Geol.*, Vol. XLIII (1935), pp. 1–26.

[17] *Ibid.*, pp. 25–26.

[18] M. P. Billings, "Regional Metamorphism of the Littleton-Moosilauke Area, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 559.

[19] T. F. W. Barth, "Structural and Petrologic Studies in Dutchess County, New York, Part II: Petrology and Metamorphism of the Paleozoic Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), pp. 775–850.

[20] *Ibid.*, p. 829.

rock into porphyritic granite. The process postulated is metasomatic alteration of quartzite into igneous-like material through the agency of pervasive emanations from a magma crystallizing as granodiorite.[21]

For the origin of the Mattagami gneiss the writer favors a hypothesis quite like that proposed by Stark for the origin of the Sawatch migmatites.[22] The chief difference is an even greater amount of hydrothermal activity in the formation of the Mattagami rock. The magma apparently expended its intrusive power rather early, and a comparatively thick shell of quartz-diorite crystallized in the magma chamber while the migmatized zone was forming. The migmatite was not intruded by magma but was flooded by emanations from the batholith, which added microcline and caused the hydrothermal alteration of the quartz-diorite shell and brought about the formation of the replacement apophyses, the pegmatites, and the quartz veins in the gneiss.

The reason for the immensely greater amount of contact metamorphic migmatite north of Mattagami Lake than around the borders of the Olga Lake batholith is probably because the Mattagami gneiss is above a batholith similar to the Olga Lake one, and solutions naturally rose, causing much greater changes above the magma than beside it.

[21] Alfred L. Anderson, "Contact Phenomena Associated with the Cassia Batholith, Idaho," *Jour. Geol.*, Vol. XLII (1934), pp. 376–92.

[22] Stark, *op. cit.*, p. 25.

ICE FLOWAGE AS REVEALED BY GLACIAL STRIAE

MAX DEMOREST
Princeton University

ABSTRACT

Ice flowage in response to the laws of fluid mechanics is shown by analyses of deflection striae found on the exposed floor of the Clements Glacier in Glacier National Park. This is particularly well shown at places where the ice has moved across angular steps and small transverse trenches in the glacier floor. At such places deflection of the ice resulted from differential pressures, which in turn resulted from flow at differential velocities. At several localities it was discovered that this mechanism had been capable of forming eddy-like currents in the ice.

An attempt is made to ascertain the minimum thickness of ice necessary to produce such flow. It is found to be between 100 and 200 feet. It is assumed that 150 feet is a reasonable figure. This corresponds to a pressure of 4 kg. per cm.^{2}

INTRODUCTION

Glacial striations have long been used to show the directions of glacier motion, but seldom, if ever, has it been realized that they might also be used to show something about the *manner* of glacier motion. That the latter is also true was made obvious to the author when he visited the Clements Glacier in Glacier National Park during the summers of 1936 and 1937. This glacier is located on the continental divide at the east foot of Clements Mountain, a mile west of the highway at Logan Pass. It is not a true glacier but more accurately a remnant of glacier ice which is rapidly disappearing.

Sometime within the very recent past a true glacier existed here. This is shown by the well-established moraines that nearly surround the abandoned glacier bed, and by the fact that both the moraines and the glacier bed are practically unweathered and free of vegetation. The surrounding land, beyond the lower limits of the moraines, offers a decided contrast, for there vegetation obscures most of the level rock surfaces, and even the barren outcrops are so weathered that few if any striae remain.

That a true glacier and not just a larger remnant of dead ice occupied this area is proved by the numerous striae on the abandoned glacier floor and by some faceted and many striated pebbles in the moraines.

The bed rock here is argillite of the Siyeh or Wallace group of the Belt series. It is flat-lying, rather thinly bedded, and broken by a rectangular system of joints that are seldom separated by more than 5 or 10 feet. As a result, excavation of the glacier bed has been by removal of roughly rectangular pieces, making the present surface a series of steps which ascend with increasing steepness from the moraines to the small ice remnant at the foot of the headwall (see Fig. 1). This increasing steepness results from the fact that near the moraines the risers of the steps are low, from 1 to 2 feet high while the treads are broad, usually as much as 20 or 30 feet. From here toward the headwall the risers increase in height to as much as 15 or 20 feet, while the treads become narrower, so that near the ice remnant few are more than 10 feet across.

The striations indicated on the topographic map (Fig. 2) give the directions of ice motion across the glacier floor. These striae were all measured near the downstream edges of the treads of the steps where movement was unobstructed and undeflected.

Other striae cut in places where the ice motion was obstructed or deflected give evidence of the manner of glacial

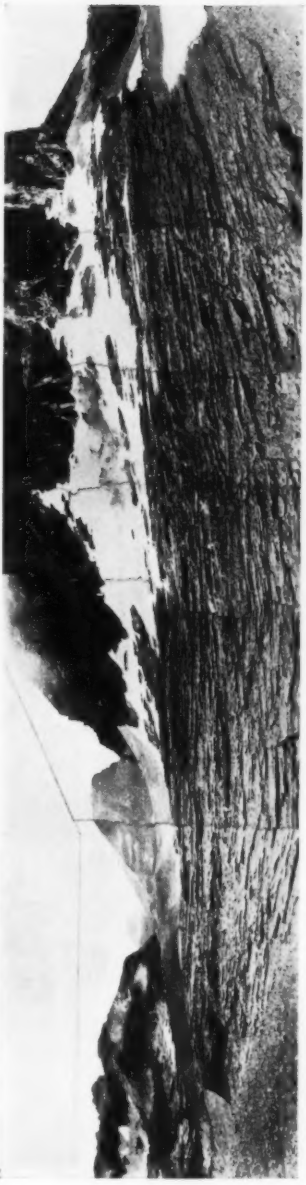

FIG. 1.—Panoramic view of the Clements Glacier from the north moraine

movement which, from the evidence given below, seems to have been by plastic flowage.

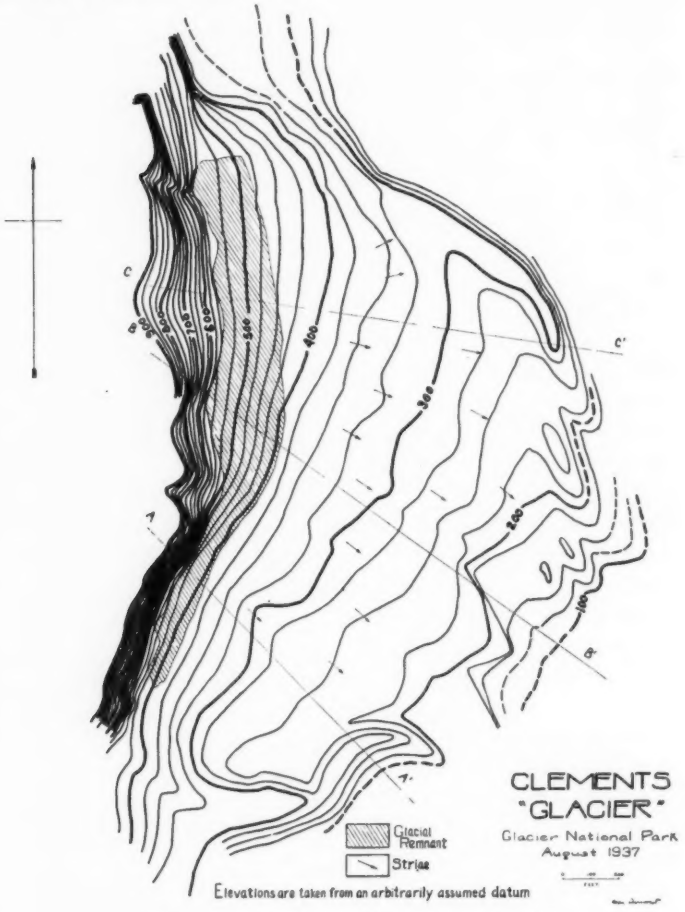

FIG. 2.—Topographic map of the Clements Glacier

The author does not intend to infer that ice flowage has not previously been demonstrated. Much material has been published on this subject, and some writers have extensively discussed the me-

chanical and physical processes by which flow probably takes place.[1] The present object is simply to call attention to further evidence of flowage that has hitherto been overlooked.

The striation phenomena that comprise this evidence are all produced by ice which was deflected from a straight line of movement. They can be described and analyzed most easily if divided into four types which will be referred to as follows: (1) striae revealing decelerated flow; (2) striae revealing deflection within transverse trenches; (3) striae revealing deflection parallel to oblique steps; and (4) striae revealing eddy-like currents.

DESCRIPTIONS AND ANALYSES OF DEFLECTION STRIAE

1. *Striae revealing decelerated flow.*—Examples of this type of striae are shown in Figures 3 and 4. They reveal the manner of ice motion in descending from one step to another, for they are cut on a vertical face which lies parallel to the direction of ice motion and extends downstream, perpendicular to one of the risers of the steps. The step is thus transverse to the direction of ice motion. This relationship is shown most clearly in Figure 3, where the step has been sketched in. The ice moved from right to left, parallel to the vertical face (*A*) and perpendicular to the step (*B*) over which it descended. Thus the striae cut on (*A*) are in effect a diagram showing, in longitudinal section, the lines of movement of the ice in its descent over the step.

The ice, in moving over the lip of the step, cut a relatively thin band of closely spaced striae on the vertical face (*A*), Figure 3. This was probably due to two factors: first, the bottom few inches of the ice was charged with a relatively large amount of debris; and, second, at this point the ice was moving more rapidly than at points either upstream or downstream from it. The greater content of

[1] L. Hawkes, "Some Notes on the Structure and Flow of Ice," *Geol. Mag.*, Vol. LXVII (1930), pp. 111–23; R. S. Tarr and O. D. von Engeln, "Experimental Studies of Ice with Reference to Glacier Structure and Motion," *Zeitschrift für Gletscherkunde*, Vol. IX (1915), pp. 81–139; O. D. von Engeln, "The Motion of Glaciers," *Science*, Vol. LXXX (1934), pp. 401–3. (Criticism by R. T. Chamberlin, Vol. LXXX, pp. 526–27; and answer by Von Engeln, Vol. LXXXI [1935], pp. 459–61); see also references given below to work by T. C. Chamberlin, R. T. Chamberlin, R. M. Deeley, and H. Hess.

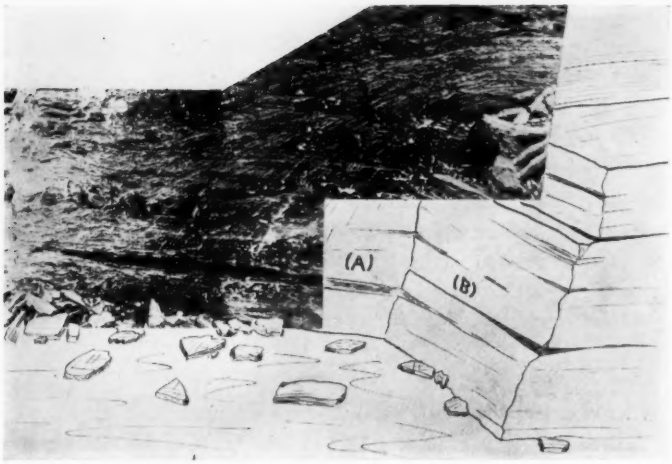

FIG. 3.—Striae revealing decelerated flow of ice in its descent over a step. Face (*A*), parallel to the direction of ice motion, is vertical and perpendicular to the step riser (*B*). The fingers at the lip of the step give the scale.

FIG. 4.—Striae revealing decelerated flow. The rock faces are again lettered as in Fig. 3.

debris should be expected because debris was probably more available to the sole of the glacier. The more rapid movement is explained by the fact that the step was a constriction of both the cross section and the longitudinal section of the glacier, thus causing ice at the lip of the step to be thinner than at any point either upstream or downstream from the lip. This constriction is explained by the relationship of the profile at the upper surface of the ice to the profile

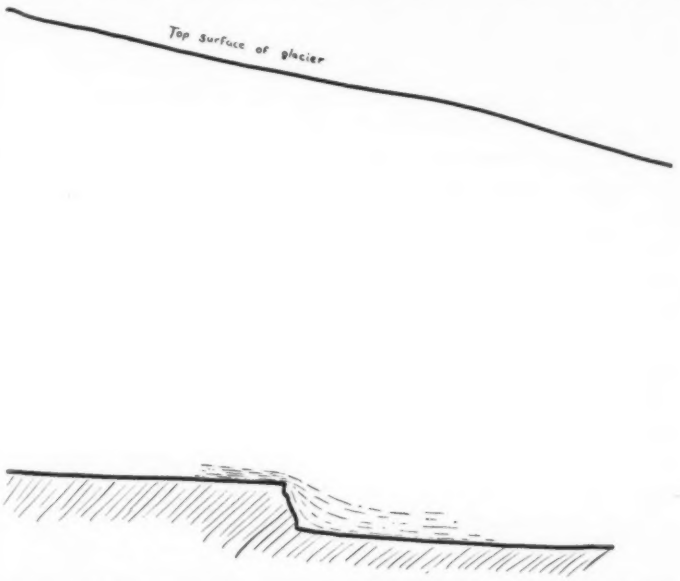

FIG. 5.—Schematic diagram to illustrate the reduction and increase in the thickness of ice as it passes over a step.

across the step (see Fig. 5). Since the surface profile slopes rather gently downstream while the tread of the step is nearly flat, the ice thins toward the lip of the step by an amount proportional to the slope of the surface profile. However, as the lip of the step is passed, there is a very sudden increase of ice thickness due to the step-down at the bottom of the ice without a corresponding step-down at the surface. Since any constriction of a flowing body causes an increase of velocity, it follows that the ice should have moved more rapidly over the lip of the step. Conversely, since an increase of the cross

section causes a decrease of velocity, it also follows that the ice was very suddenly slowed down or decelerated after passing the lip of the step. A record of this deceleration is found on the vertical face where the striae cut by the debris-filled bottom few inches of ice spread out fanlike, becoming more widely spaced as they descend over the step.

It may be contended by some that such a step as this does not constitute a true constriction in the cross section of flow, for the upper surface of the ice is unconfined and, therefore, free to adjust itself to changes in the level of the glacier floor. With regard to large-scale features in the floor, there is no doubt that this sort of free adjustment does take place; yet, in the case of small-scale irregularities, observations of existing glaciers indicate that they are not revealed at the upper surface. This lack of surface adjustment to such irregularities may be explained, in part, as a result of inertia, for the hydrostatic head which causes motion in the ice, expends less energy in producing rapid motion in the plastic bottom part than in overcoming the weight and inertia of the overlying mass of ice.

It may also be contended that a small step at the bottom of a glacier 200 feet thick would hardly be noticeable as a constriction. Yet it must be kept in mind that the greater plasticity of the basal ice makes it reasonable to consider the bottom few feet of the glacier as a relatively shallow stream of confined flow in which the step becomes a constriction of large proportion.

In further analyzing these striae, attention must be given to the fact that the ice followed streamlines in passing over the step. Thus, the more rapidly moving, though decelerating, ice overrode a triangular space close to the bottom of the step in which there was a gradually decreasing differential flow or relatively inactive ice.

This, and the fact that decelerated flow is demonstrated by the fanning-out of the striae, seems to be proof that the ice which caused the striations was moving in response to the laws of fluid mechanics.

In discussion with the author, others have argued that such striae might have been cut by ice which moved as an elastic solid along planes of mechanical shear. According to this idea the relatively stagnant ice at the foot of the step would have been passed over by differential shear on multiple planes. However, this seems improb-

able when one considers that the divergence of the striae could hardly have been produced, even on multiple-shear planes, by a substance that was not plastic. In addition, inspection of the photographs, Figures 3 and 4, reveals that some of the striae describe long reverse curves in descending over the step, while others, especially those few that diverge sharply downward from the generalized line of flow, follow curves that are decidedly convex upward and forward. (The further significance of this is discussed below.) Mechanical shearing on surfaces of this sort would be impossible, for

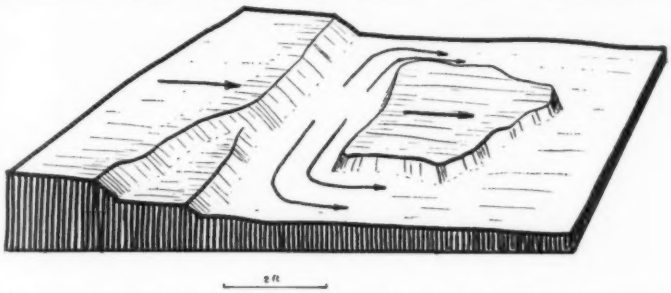

FIG. 6.—Sketch showing the deflection associated with a small trench which lay transverse to the direction of undeflected ice motion.

the ice along and between the shear planes would have to be plastically bent as it moved over such sinuous surfaces.

Thus, rather than differential mechanical shear on multiple planes, it may be concluded that the ice moved by some sort of viscous flow.

2. *Striae revealing deflection within transverse trenches.*—This type of striae, which is produced wherever small trenches lie transverse to the direction of glacier movement, is best shown in the sketch, Figure 6, and the photographs, Figures 7 and 8. Unfortunately, clean surfaces in positions of this sort were not found, so the striae show but poorly in the photographs. In Figure 8 they have been chalked in. The trench shown there is not open at both ends, so that deflection striae are developed in one direction only. The trench in Figure 7, however, is entirely open, though but one end of it is seen in the photograph. The sketch is an approximate-scale drawing of this same trench, and shows it in its entirety.

FIG. 7.—View downstream across the near end of the trench sketched in Fig. 6. Chalk lines have been drawn on the rock surface to bring out the direction of the deflection striae. Ice motion was away from the observer, parallel to the rod.

FIG. 8.—A small trench lying transverse to the direction of ice motion. Striae are chalked in. Ice motion was to the right. Arrow indicates downstream direction.

The fact of ice deflection from such transverse trenches is apparent without further discussion and, the author believes, offers in itself a convincing demonstration of ice flowage. There are, however, some points to which attention should be drawn.

One is the manner in which striae are cut on the downstream walls of the trenches. Striae that are cut along the downstream wall of the trench shown in Figure 8 slope gently upward from the middle of the trench toward the open end of the trench, some of them passing over the wall onto the upper surface of the downstream block without having to pass completely around the end of the block. This also calls attention to the striae that are cut in the rock of the upper surfaces, both upstream and downstream from the trench. They are all parallel, being undeflected at any point. This condition, together with the fact that the upstream wall of the trench is higher than the downstream wall, seems to indicate that ice, coming from upstream, did not abut directly against the obstructing block of the downstream wall but rather moved without deflection across and above the less active ice which filled the trench. Thus these apparently simple deflections must be explained by something other than the mere presence of an obstructing block.

This explanation can again be found in an appeal to fluid mechanics. It is well known that in a moving fluid the pressure varies inversely as the velocity. Familiar demonstrations of this are seen in atomizers, paint sprayers, and insect sprayers where a fluid (in this case, air) is forced by a pump through a jet so that a rapidly moving stream of air passes over a tube whose lower end is immersed in the fluid to be sprayed (in this case a liquid). The reduction of pressure in the rapidly moving jet of air causes the liquid to rise to the head of the tube where it is caught in the jet and blown away.[2] The fact of interest here is that the differential movement produced by the rapidly moving current of air causes a reduction of pressure within the current and an indraft toward it. Generalizing from this, one may say: differential flow in any substance causes differential

[2] Analogy to an example of this sort may be objected to on the grounds that kinetic energy plays a role in the mechanism of such rapidly moving fluids, while in such slowly moving substances as ice kinetic energy is too small to be considered. Nevertheless, the relationship between differential pressure and differential flow is clearly expressed, and the example is used for that reason.

pressure with a gradient toward the more rapidly moving part. Another statement implying the same thing is that an increase of velocity causes a decrease in the cross section of flow. In the discussion of the first type of striae the converse of this was expressed in stating that "any constriction of the cross section of a flowing body causes an increase of velocity" and, we may add, a decrease of pressure. All these statements are essentially expressions of the same fundamental principle.

The application of this principle to the striae under consideration is apparent. Ice in the trench was relatively inactive as compared to that which moved unobstructed past the ends of the trench and over the top of it. There was thus a pressure gradient toward the more rapidly flowing ice in those places. Apparently a greater gradient existed between the middle and ends of the trench, where gravity could not oppose it, than between the comparatively stagnant ice of the trench and the more rapidly moving overriding ice. This is revealed by the fact that most of the striae may be followed toward the ends of the trench where they merge with those cut by the passing ice; and also by the few striae that do rise over the outer ends of the downstream wall to join the undeflected striae on the upper surface. The very low angle at which these striae rise signifies that the ice in the trench was moving with a strong lateral component and a weak upward one.

The weakness of the upward component is to be expected not only because movement in that direction was opposed by gravity, but also because the surface of flow across the top of the trench should have been less continuous than that of the ice which moved more rapidly past the ends of the trench. The reason for this is found in the fact that the ice in the trench could not move out toward the ends or over the downstream wall without being replaced by fresh ice. The fresh ice must have come into the trench over the upstream wall, particularly near its middle. In short, the strong, gradient toward the ends of the trench forced a downflow in opposition to the gradient established toward the overriding ice. Had the overriding ice produced a gradient stronger than that toward the ends of the trench, the opposite would no doubt have been the case, thus causing a greater withdrawal of ice over the middle of

the downstream wall, and a compensating indraft at the ends of the trench in opposition to the gradient in that direction.

Analysis of this second type of striae also gives evidence that the ice was moving by some sort of viscous flow in response to the laws of fluid mechanics.

Similarities of the trench and the step.—The only essential difference between the transverse trench and the step described in the first section is that the step lacks the downstream wall. Otherwise conditions of flow were very similar. In the case of the trench there was a current of more rapidly moving ice which overrode less active ice. In the case of the step this was also true. At the trench there was a differential pressure established by the differential flow, and a consequent deflection of ice. The same was true at the step, with the exception that there was no deflection. This was due to the lack of a downstream wall. Without such a wall there were no open ends such as exist in the case of the trench; and without open ends there could have been no pressure gradient built up in a direction transverse to flow. Thus it follows that the pressure gradient established in the downstream direction toward the overriding ice was unopposed. As a result the less active ice must have been withdrawn, without deflection, over the nonexistent downstream wall. In short, there was no deflection because it was possible for the less active ice to be withdrawn along the surface of the lower tread in a direction parallel to movement of the undeflected ice.

As in the case of the trench, there must have been a compensating indraft to replace that ice which was withdrawn; again it was by way of the upstream wall, i.e., over the lip of the step. Close inspection of Figure 3 shows this clearly. On the wall (*A*) are well-defined, highly convex striae which descend nearly parallel to the face of the riser. These were cut by debris carried in the compensating indraft of ice (and are the highly convex striae previously referred to.)

Here, where the striae show so plainly, it has no doubt been noticed by the reader that there could have been no sharply defined limit between the active and the inactive ice but rather a gradually decreasing differential flow with that ice at the bottom of the step moving most slowly. This, in combination with the vertical spreading of the lines of flow, which revealed decelerated motion, brings a

certain vagueness to the definition of overriding ice as distinct from overridden ice. This same vagueness applies to such phrases as "withdrawal of less active ice" and "compensating indraft," for the limits of the withdrawn and the indrawn ice are not sharply defined. Yet the validity of these expressions in explaining the mechanism of flow is hardly to be questioned. On the contrary, it is this very lack of sharp definition in differential flow that distinguishes plastic and viscous yielding from failure by fracture and shearing.

3. *Striae revealing deflection parallel to oblique steps.*—These striae are cut on and at the foot of the risers of a few of the low broad steps which are at a distance from the headwall. The steps are those less numerous ones which lie in such positions that the ice descended obliquely over them at but a small angle, so that the vertical face which forms the riser approaches parallelism to the general direction of undeflected flow. In the five cases that were observed the angular difference between the direction of undeflected flow and the trend of the riser was between 12° and 26°.

Typical of such steps and their associated striae is the one shown in Figures 9 and 10, which will be explained and described in detail. The riser is a joint face 2.2 feet high. Except for a few striae, it is practically uneroded. The ice descended obliquely over the step from left to right. Striae cut by undeflected ice on the tread at the top of the riser bear N. 43° W. and continue in parallel lines to the very edge of the step. The bearing of the riser is N. 60° W., a difference of 17°. Striae cut on the lower tread within 3 or 4 inches of the foot of the step bear exactly parallel to the riser. At a distance of 9 inches from the foot they bear N. 57° W., and at 18 inches they are again bearing N. 43° W., parallel to those on the upper tread.

These figures reveal that the deflected ice moved along the face of the riser in a direction parallel to it and that at progressively greater distances from the foot of the riser there was less and less deflection, until, at a distance of 18 inches,[3] the striae are again oriented in the same direction as those on the upper tread.

Further interesting facts regarding the deflected ice near the face

[3] A distance of 62 inches when measured in a direction directly downstream from the foot of the riser.

of the step are shown by the long clean-cut striae which appear on the face of the riser in Figure 9. These striae ascend at a moderate angle to the right, the downstream direction, thus showing that the

FIG. 9.—The riser of a step over which ice descended obliquely from left to right. Notice that the striae point upward in a downstream direction.

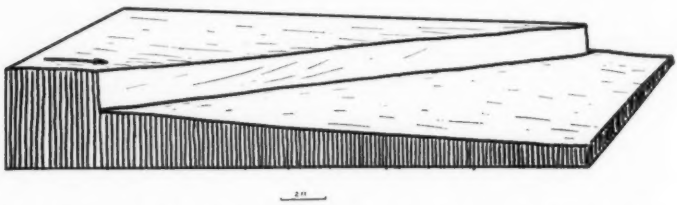

FIG. 10.—Sketch of the oblique step shown in Fig. 9 picturing the relationship of the striae on both the upper and the lower treads.

ice which moved along the riser was rising rather than descending. This was in response to a pressure gradient established toward the more rapidly moving ice at the lip of the step. The fact that this gradient was not opposed and reversed by a compensating down-

draft, as was the case with the transverse steps and trenches, can be accounted for only by assuming that a compensating indraft was more available from elsewhere. It is logical to assume that the movement of ice parallel to the riser constituted this more available indraft.

Judging from these considerations, it is apparent that the chief difference between the transverse and oblique steps is to be found in the manner by which the compensating indraft takes place. At first thought it might be suggested that the mere fact of obliquity makes this difference inevitable, for, since the undeflected movement has a strong component parallel to the step, it should favor a flow of ice along the face of the riser, thus promoting lateral indraft and eliminating any need for downdraft from over the top of the step. To a large extent this is true, yet one must seek further to account for the supply of ice which flowed along the face of the step, for, if no such supply had been maintained, the gradual but continuous withdrawal of less active ice from the downstream side would soon have forced an indraft from over the top of the riser. However, as indicated by the striae on the face of the step, this supply was maintained, and at the locality of Figure 9 it must have come from along the riser at a point farther to the left, i.e., upstream; and the ice there must have come from still farther upstream, and so on until finally the end of the riser was reached. There the lateral source of supply was necessarily at an end, with the result that downdraft over the top of the riser was inevitable. Not only was this change necessitated by the fact that the step was at an end but, in addition, it was greatly favored by the fact that the gradient of the glacier floor is steeper. Ice descending on this gradient had a strong moment of inertia, giving it a strong downward component of force which was effective until the ice became adjusted to flow on the less steeply sloping surfaces of the lower broad steps. Thus, in effect, there was a factor tending to force ice down over the top of the riser at its upstream end, and probably aiding greatly in the maintenance of the deflected flow along the downstream part of the riser.

This explanation of the deflection striae associated with oblique steps appears to be complete, and, as before, it is in keeping with the laws of fluid mechanics.

4. *Striae revealing eddy-like currents.*—This fourth type of phenomenon again reveals the same fluid mechanism, but in a more spectacular way, for it demonstrates that flowing ice may be thrown into eddies[4] if sufficiently disturbed or obstructed.

The best example that was found of these striae is shown in the photograph, Figure 11. The sketch, Figure 12, is included to show, better than in the photograph, the geometric relationships of the adjacent rock surfaces.

The eddy is revealed by the striae cut on the end wall of a trench which lay transverse to the direction of undeflected ice motion. In the photograph this direction is indicated by the stadia rod which was laid parallel to it, and in the sketch by the heavy arrow. The trench is about 2.5 feet wide and averages about 3 feet deep with the upstream wall 18 inches higher than the downstream wall. Its length is approximately 3 feet with the floor continuing at an even level out onto an extensive surface on which ice moved, without deflection, past the open end of the trench.

If the trench were filled with solid rock to the level of the downstream wall, the higher upstream wall would constitute a transverse step over which ice would have descended, leaving relatively inactive ice at its foot, as described earlier in the paper. The trench may therefore be thought of as having underlain such a zone of inactive ice. Thus, the less active ice that filled the trench and that at the foot of the step were continuous. Movement of ice from and within this less active zone was necessarily determined by the pressure gradients established toward the more rapidly moving ice. Differential flow past the open end of the trench caused withdrawal of large quantities of ice at a low level. This is indicated by striae, cut on the downstream wall of the trench, which descend at a steep angle toward the outer end. The necessary compensating indraft must have been established where the pressure gradient was least. This was above the trench where the ice, in descending over the

[4] Such eddies are not exactly the same as those formed in rapidly moving water, though they may, in part, be explained by the same line of reasoning. The significant difference arises from the fact that the more familiar eddies in water are accompanied by *turbulent* flow, while these in ice are accompanied by *laminar* flow. Ice is not capable of flowing rapidly enough to become turbulent.

FIG. 11.—Striae revealing an eddy-like current. Ice moved to the left, parallel to the rod.

step fanned out in decelerated flow, thereby creating a smaller differential of flow, and a smaller pressure gradient. Part of this ice which descended over the step with decelerated flow undoubtedly crossed over the top of the trench withdrawing some of the less active ice, without deflection, onto the upper rock surface downstream from the trench. However, larger quantities of ice must have

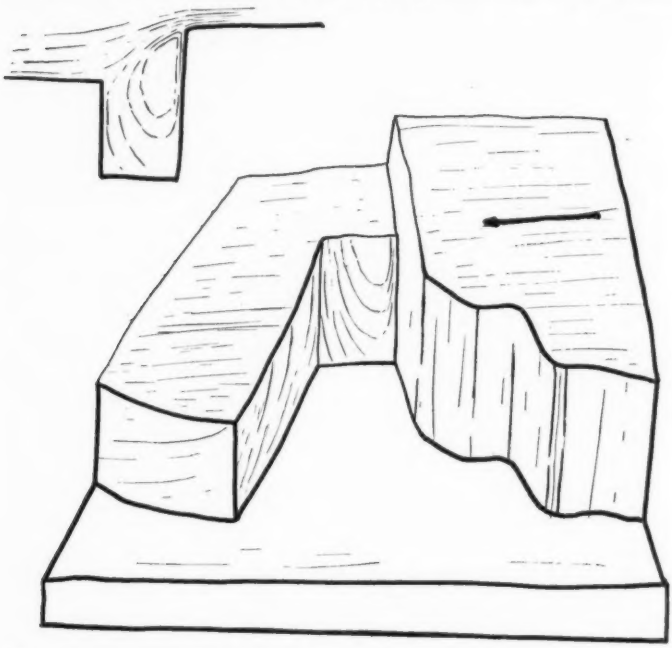

FIG. 12.—Diagrammatic sketch of the eddy-like current striae showing their full course. At top, the lines of flow of the ice in its passage over and into the trench.

been deflected from the lower part of the decelerated flow and drawn into the trench along its downstream wall, thus compensating for the outflow at the open end.

The lowering of the pressure gradient toward the overriding ice was proportional to the amount of deceleration. Therefore, at the top of the step, where no deceleration had taken place, the gradient must have been maintained to a higher degree. In fact, at that

point it must have been higher than anywhere else in the system, for ice next to the upstream wall should have been least active and that of the overriding ice at the lip of the step most active. An updraft should therefore have been expected along the upstream wall in response to this differential. Unfortunately, the striae that should mark such an updraft are absent, owing to disintegration of the rock surfaces along this critical place. Nevertheless, deflection striae on the end wall indicate that such an updraft did occur. These are the striae which curve downward and to the right in the photograph, Figure 11, having been cut by ice of the indraft which was deflected in an upstream direction toward the trench wall. Such a deflection can be explained only as a response to a pressure gradient directed toward the upstream wall, and such a gradient can be explained only by a more rapidly moving current of ice ascending along the wall. This ascending current, to repeat, is explained by the high differential that existed at the lip of the step. To complete the circuit of the eddy, the ascending ice, on reaching the lip of the step, was drawn into the flow of overriding ice which decelerated in its descent and was, in part, drawn back into the trench on the downstream side. The cross section at the top of Figure 12 shows the nature of the lines of flow in and about the eddy.

The reader may very well raise a question as to why a similar eddy was not formed by the ice which descended in decelerated flow over the transverse step first discussed. It is true that at that place, also, the pressure gradient toward the decelerated downstream part of the overriding ice was less than that in an upward direction toward the lip of the step. Yet an updraft toward the lip did not occur but, rather, just the opposite. A downdraft was established in its place. This was explained as a result of withdrawal of the less active ice in a downstream direction. Inertia probably favored this withdrawal, prohibiting any back-flow that would have been necessary for the maintenance of an updraft.

The development of an eddy in the case of the combined step and trench was made possible by the greater withdrawal of inactive ice at a low level through the open end of the trench. This was sufficient to deflect a large part of the overriding ice into the trench as a compensating indraft along the downstream side, thereby

bringing a continuous supply of less active ice into position for further diversion to the updraft. Thus the withdrawal of ice at a low level through the open end of the trench was an essential priming force in the development and maintenance of the eddy.

Since eddies in other media are so often associated with rapid flow, it should again be noted that there is no intention to imply rapid flow here. Differential flow—not rapid flow—was responsible for these deflections.

ICE FLOW

Flow in fluids, such as liquids and gases, results in differential molecular movements. It has been argued that ice cannot be made to flow in a true sense, since its solid crystalline character prohibits such molecular movements. If the term "flow" can be restricted to those deformations which take place by intermolecular movements, then the argument is valid. However, the term "flow" seems more aptly applied to any deformation which takes place in response to the laws of fluid mechanics, regardless of whether the differential movement is between free molecules or between crystalline aggregates of molecules. In this connection it is well to point out a term used by R. M. Deeley in 1895.[5] Discussing the viscosity of ice and the fact that differential movement is between crystalline particles, he wrote: "Its viscosity appears to be rather a molar than a molecular phenomenon." According to *Webster's New International Dictionary*, the word "molar" as used in this sense is defined as follows: "Of or pertaining to a mass of matter;—said of the properties or motions of masses as distinct from those of molecules."[6] It is therefore suggested that, if one wishes to distinguish the flow of solid ice from the molecular flow of fluids, the term "molar flow" or "molar viscosity" be used. This suggestion is made only because it seems to clarify the distinction between flow of solids and of fluids, and not with any idea that these terms should supplant the terms "plastic flow" and "solid flow," which have been long in use.

An occasionally quoted objection to theories of ice movement by flowage is that they do not account for striae, for it is said that any

[5] "The Viscous Flow of Glacier Ice," *Geol. Mag.*, Decade IV, Vol. II (1895), p. 413.

[6] The word is derived from the Latin *moles*, meaning "mass."

substance weak[7] enough to flow should be incapable of holding tools firmly enough and steadily enough to produce striations. The fact that striations have themselves been used in demonstrating ice flowage seems to be sufficient evidence that the objection is invalid. Perhaps the fallacy lies in supposing that the cutting tools must necessarily be firmly held. It is known that heavy rocks sliding down a slope will cut striae. In a similar way striae have been cut by rocks carried in snowslides.[8] Apparently, the important thing in the cutting of striae is that heavy tools should move across a bedrock surface. The manner in which the movement is imparted is less significant, though it may modify the result. In the case of a glacier the pressure that causes movement by flowage is in part a pressure adding weight to the tools with the result that even a small pebble may become effective in producing striae.

In discussing ice flow at such length, the author may have given the impression that he believes flow to take place to the exclusion of shearing and fracturing. Such an impression is not at all intended, for he rather fully agrees with the view of R. T. Chamberlin[9] as expressed in his most recent discussion of glacier movement. There Chamberlin points out that both modes of movement may be effective throughout the thickness of a glacier, but with fracture and shear dominant at and near the surface, and flow dominant below a certain level which may vary with pressure, temperature, and the duration of stress applications. Thus the upper several feet of a glacier constitutes a zone wherein fracture is dominant. Below this there is a transitional zone toward deeper ice in which high hydrostatic pressure prohibits open fractures or cavities and favors flow as the dominant mode of motion.

PROBABLE DEPTH AT WHICH FLOWAGE BECOMES DOMINANT

At the time of the cutting of the various striation phenomena described above the ice must have been so thick that flow was the

[7] Ice is weak only in that it is deformed by low differential pressures when under sufficient hydrostatic pressure, or when the differential pressure is applied very slowly; yet it is decidedly rigid in that it is an effective transmitting medium for seismic waves.

[8] J. L. Dyson, "Snowslide Striations," *Jour. Geol.*, Vol. XLV (1937), pp. 549–57.

[9] "Glacier Motion as Typical Rock Deformation," *Jour. Geol.*, Vol. XLIV (1936), pp. 93–104.

dominant mode of deformation at the bottom of the glacier. Otherwise such well-defined evidences of flow could hardly have been produced.

An attempt has been made to determine what minimum thickness of ice must have been necessary to produce such dominant flow. This was done by constructing a surface profile such as the glacier probably had at the time it was advanced to the position of the present moraines and superposing this profile on the topographic sections of the glacier bed (see Fig. 13). Undoubtedly, the thickness as thus determined is greater than the minimum necessary to cause flowage, for it is hardly likely that flow took place only when the glacier was at its maximum advance. Rather it is probable that the basal ice continued to flow for an indeterminable time during the recession of the glacier. Flow would have ceased to be dominant only when thinning of the ice brought the upper zone of dominant fracture, or at least the transitional zone between dominant fracture and flow, in contact with the glacier floor. In the transitional zone it is probable that shear, without open fractures, is dominant and that flow becomes less and less effective as the zone of dominant fracture is approached.

The surface profile was constructed from the composite of the seven glacial profiles shown at the top of Figure 13. These profiles were all taken from the work of Hans Hess[10] who has made many careful measurements of Alpine glaciers. Conditions of precipitation and temperature in the Alps are sufficiently similar to those of Glacier Park that no great error should have been introduced because of differences in location and climate.

In placing the glacial profile over the topographic section, the lower termination of the profile has been placed at the top of the moraine. This again probably introduces an error of too great thickness, for it is more likely that such a profile would originate at a level some place within the moraine.

The maximum thickness of ice as thus determined is 200 feet, and, for the reasons given above, it may be assumed that flow took place under ice of less thickness. How much less can only be conjectured,

[10] Taken from different articles appearing in various volumes of *Der Zeitschrift für Gletscherkunde.*

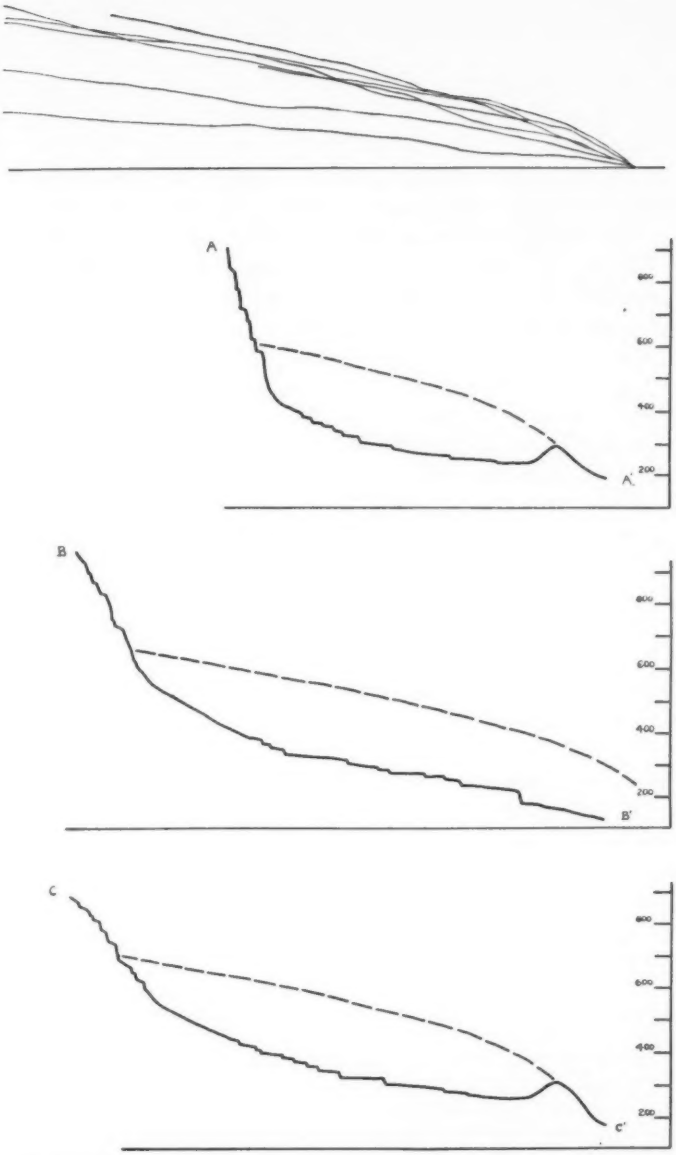

FIG. 13.—Topographic sections across the abandoned glacier bed with the probable glacial profile superposed to show the approximate thickness of ice at its maximum. At top, the composite of Alpine glacier profiles from which the superposed profile was taken.

yet a limit is suggested by the seismic work done on Alaskan glaciers by R. P. Goldthwait.[11] He determined that the maximum depth of crevassing in the South Crillon and Klooch glaciers was about 100 feet (30 meters). In suggesting that a similar depth of crevassing might be found in the glaciers of Glacier Park, it should be pointed out that the temperature conditions of the south Alaskan coast and of the Park are quite similar. The difference in the degree of glacierization[12] in the two places is probably due to a difference in precipitation rather than in temperature.

Below the 100-foot zone of crevasses, or dominant fracture, it may be supposed that there was a transitional zone of dominant shear before reaching the zone of dominant flow. Thus the minimum thickness of solid ice necessary to produce dominant flow must have been somewhat more than 100 feet and, as pointed out above, certainly less than 200 feet. Probably 150 feet may be taken as a close approximation. In areas of névé accumulation the depth would no doubt be greater, owing to the lesser density of the overlying ice.

Stated in terms of pressure, if 150 feet (45 meters) of solid ice may be taken, the mass overlying one square centimeter would be: 4500 (cm.) $\times$ 0.91 (the density of ice) = 3995 grams. In round numbers, 4 kg. per cm.^{2} is the approximate pressure necessary to produce dominant flow.

This same measurement will apply to other glaciers where comparable temperature conditions are found at depth within the ice. Sound arguments given by Chamberlin, by Deeley, and by Hess[13] indicate that the temperature within all temperate-region glaciers must be about the same. This is particularly true at the bottom of glaciers where the temperatures must be at about the melting-point

[11] "Seismic Sounding on South Crillon and Klooch Glaciers," *Geog. Jour.*, Vol. LXXXVII (1936), pp. 496–517.

[12] Following the distinction proposed by C. S. Wright and R. E. Priestley, *Glaciology* (British [*Terra Nova*] Antarctic Expedition, 1910–1913 [London: Harrison, 1922]), p. 134. They suggest that the term "glaciation" be applied to the effects of ice action and "glacierization" to the actual inundation of land by ice.

[13] T. C. Chamberlin, "A Contribution to the Theory of Glacial Motion," *Decennial Publications of the University of Chicago*, Vol. IX (1904), pp. 193–206; R. M. Deeley and P. H. Parr, "The Hintereis Glacier," *Philosophical Magazine*, Vol. XXVII (6th ser., 1914), pp. 153–76; Hans Hess, "Das Eis der Erde," *Handbuch der Geophysik*, Vol. VII, Lief. 1 (Berlin, 1933), pp. 36–46.

of ice. Thus it would seem that the pressure figure given has a wide enough significance that it may be applied to all temperate-region glaciers.

CONCLUSIONS

Ice under sufficient pressure flows in response to the laws of fluid mechanics, as demonstrated by analyses of striae found in the bed abandoned by the Clements Glacier.

The least thickness of solid ice necessary to cause such flow to become the dominant mode of movement is probably close to 150 feet, which corresponds to a pressure of 4 kg. per cm.^{2}

ACKNOWLEDGMENTS.—For critical reading of the manuscript the author is indebted to the following men of the geology department at Princeton University: Professors Paul MacClintock and Erling Dorf, and Mr. F. B. Van Houten, a fellow-graduate student.

For aid in mapping the abandoned glacier bed thanks are due to Warner S. Goshorn and Robert M. Johnson, undergraduate students at the University of Cincinnati and Cornell University, respectively.

KEY TO PAPERS PUBLISHED BY AN INSTITUTE FOR THE STUDY OF MODERN SEDIMENTS IN SHALLOW SEAS

WALTER H. BUCHER
University of Cincinnati

ABSTRACT

The aims of the institute, "Senckenberg-am-Meer," on the shore of the North Sea at Wilhelmshaven, and its equipment and collections available to visitors, are first set forth. Then the contents of 120 papers issued in connection with the institute are briefly summarized as a guide to a large number of data of great value to the student of sedimentation, under five major headings: "I. Modern Marine (Shallow-Water) Sediments"; "I*a*. Quaternary Stratigraphy and History of the German North Sea Coast"; "II. Modern Marine (Shallow-Water) Life"; "III. Interpretation of Fossil Marine Sediments"; "IV. Interpretation of Fossil Marine Life."

THE INSTITUTE

The institute, "Senckenberg-am-Meer," on the shore of the North Sea at Wilhelmshaven, is devoted to the study of the sediments in modern shallow seas from the viewpoint of geology and paleontology. Few geologists outside Germany know that such an institute exists, and its publications are correspondingly little known. It is the purpose of this paper to set forth the aims of the institute[1] and the facilities which have been created and to summarize the contents of the publications that have so far been issued.

The full title of the institute is "Forschungsanstalt für Meeresgeologie und Meerespalaeontologie der Senckenbergischen Naturforschenden Gesellschaft zu Frankfurt am Main." As the title indicates, it owes its existence to the spiritual and material resources of a civic society of natural history, the Senckenbergische Naturforschende Gesellschaft, which through its splendid museum and its scientific and popular publications exerts an influence in Germany

[1] The writer spent almost two weeks at the institute last September, going onto the tidal flats when circumstances permitted, studying the published literature, and using the files of the specialized library. He wishes to express his sincerest thanks to Professor Richter for permission to do so and to Dr. Walter Häntzschel, resident geologist, for his invaluable guidance in the field and in the library, especially also for calling the writer's attention to important papers from his personal files.

somewhat comparable to that of the American Museum of Natural History in the United States.

The idea of such a research institute arose from the fruitful studies on phenomena of tidal flats and their fossil counterparts which Professor Richter published between 1920 and 1926 (Appen. A). He realized the possibilities and eventually formulated[2] the purposes of the institute.

The shore of the North Sea offers unusual opportunities for studies of this kind. The difference between mean low and high water is great,[3] exposing at low tide exceptionally wide tidal flats (*Watten*), which form a fringe several miles in width. From the deeper parts of the shelf sea, samples of sediment and benthos can be obtained with devices that are manipulated from boats without cumbersome machinery. Methods are being worked out for obtaining samples in such a form that their stratification can be studied. The institute is not intended to add merely to the sum of oceanographical and biological data, such as are being secured by a number of organizations, but to search systematically for such features—many of them insignificant enough in themselves—as may lead to a better understanding of sediments of the geologic past.

The first purpose of the institute, then, is to make available to the research worker laboratory facilities and necessary apparatus for studies of this sort. These include, besides standard optical and chemical equipment, elutriation apparatus,[4] cutting and slide-grinding machinery, centrifuge, sediment tubes, clam-shell samplers, etc. For biological studies,[5] aquaria of different sizes, including a supply of compressed air for aeration, are available.

Since the mechanical problems of sedimentation are primarily problems of hydraulics, one of the reasons for locating the institute at Wilhelmshaven was the fact that the hydrological laboratory of the Navy is located there. The director, Regierungsbaurat Dr.

[2] See items 4 and 27 of Appen. B.

[3] 3.6 m. (11.8 ft.) at Wilhelmshaven.

[4] Two types in use: Kraus-Kopecky and Wiegner. A pipette apparatus is being purchased.

[5] The long-established biological station on Helgoland is within easy reach. Its staff of experienced workers has placed its knowledge and collections at the disposal of the institute in hearty co-operation.

Ing. Karl Lüders, not only has repeatedly put the facilities of the laboratory at the disposal of workers at the institute but has taken an active part in the investigations.

In the descriptive sciences progress is possible only to a limited extent through experimentation. The recognition of general properties and broad principles which have the character of "natural laws"[6] depends largely on the patient accumulation of materials and data, which leads to the summation of experience and the ultimate integration of knowledge. This, then, is the second purpose of the institute. Carefully designed cases house the collections of organic and inorganic materials. The archives of photographic records contain over four thousand pictures of uniform size mounted on cards and filed with complete data.

Large numbers of detailed maps of the sandbanks and tidal mud flats are available to the duly accredited worker either in the files of the institute or in those of the respective departments of the Navy yards. These maps are a most important source of information for the student of sedimentation as well as of shore processes. Two critical areas of tidal flats (Wangeroog and Old Oog) are surveyed annually on a large scale (1:15,000) by the estuary channel commission (*Strombauressort*) of the Navy yards, through a staff of about forty men. The former director of this commission, now Hafenbaudirector i.R. Dr. Wilhelm Krüger, has developed the records to their present extraordinary accuracy and, through them, has studied for decades the movements of sediments in this region. Regierungsbaurat Dr. Karl Lüders is following up these studies with great energy, as may be seen from the papers reviewed later in this paper. The emphatic support of these men and of the chief officials at the Navy Yard,[7] who recognize fully the practical value of scien-

[6] See Walter H. Bucher, "The Concept of Natural Law in Geology," *Ohio Jour. Sci.*, Vol. XXXVI, No. 4 (1936). (Reprinted in *Science*, Vol. LXXXIV, No. 2188 [Dec. 4, 1936], pp. 491–98.)

[7] It is good for us to remember that our own naval authorities are no less ready to enter into hearty co-operation in oceanographic studies whenever projects of real merit are placed before them, as is shown by the Princeton-Navy expeditions; cf., e.g., H. H. Hess, "Interpretation of Geological and Geophysical Observations," *Navy-Princeton Gravity Expedition to the West Indies in 1932* (U.S. Hydrographic Office, 1933), pp. 27–54, figs. 16 (incl. maps).

tific penetration of the problems of tidal waters, has been a powerful factor in the materialization of the plans for the institute.

It is expected that the institute will eventually extend its activities to sediments in other shallow seas. It maintains to that end an exchange with oceanographic, geologic, and biologic organizations in general[8] and is building up a library of the literature on modern marine sediments and on the interpretation of fossil sediments. Like Dr. Richter, the present resident geologist (*Leiter*) of the institute, Dr. Walter Häntzschel, is known equally for his studies of modern sediments and his analyses of features of sedimentary rocks.

Finally, an institute of this sort forms a valuable basis for field instruction. In the case of modern sediments, even more than in geology in general, photographs and descriptions cannot convey adequate understanding to those who do not know the exposed sea floor of the tidal flats from personal experience. As facilities become available,[9] professors and students of geology and biology will make use of them for occasional visits,[10] or even as a regular part of their instruction.

THE PUBLICATIONS

Ten years have elapsed since the institute opened its doors. One hundred papers have been printed in the publications of the Senckenberg Naturforschende Gesellschaft, numbered consecutively with the reference title "Senckenberg-am-Meer." The complete list of

[8] Two near-by organizations are contributing papers bearing directly on the problems on which work is focused at Senckenberg-am-Meer: (1) the Skalling Laboratory, on the Skalling peninsula in southwestern Yutland, and (2) the Institut für Meeresforschung der Universität Kiel, Kitzeberg bei Kiel. (The geological department is under the direction of E. Wasmund.) Papers from both are quoted in the body of this article.

[9] At present there are available for visitors three laboratories, each with eight working spaces, supplied with running water, gas, electricity, and compressed air (for the aeration of aquaria).

[10] The beginner can see many of the common forms of invertebrate life of the North Sea at the Civic Aquarium, which is located near the institute. For a description of a study trip which in part used the institute as a base of operations see W. E. Ankel, "Nordseefahrt und Ferienlager Giessener Biologen," *Ber. Oberhessische Gesellsch. f. Natur-und Heilkunde zu Giessen*, Band XVII (1936), pp. 120–26.

these papers is given in Appendix B. They will be briefly reviewed,[11] together with Richter's earlier papers listed in Appendix A. In the following, the small letters and numbers in parentheses refer to the corresponding items in Appendixes A and B, respectively.

I. MODERN MARINE SEDIMENTS

METHODS OF STUDY

Two methods have been described for direct *hardening of freshly collected, wet sediments* without previous desiccation. To Schwarz's older method (23) there has been added recently one devised by Goemann (99). The sample is collected in a suitably constructed copper box and is suspended by means of a sieve, box and all, in a dioxane (diethylenedioxide) solution about 3 cm. above a layer of calcium chloride which removes the water from the solution. The dioxane-impregnated sample is then placed in molten paraffin and the temperature slowly raised to 105–10° C. until the paraffin has completely replaced the dioxane which evaporates. For a box 9 × 12 × 5 cm. the treatment requires three and five days for argillaceous fine sand and highly argillaceous silt, respectively. A box 19 × 28 × 10 cm. requires six and twelve days, respectively.

Häntzschel (96) describes a useful method for securing *cross sections* of samples for close study, adapting Voigt's film method[12] to marine conditions. Eberle (22) points out that casts of delicate *tracks in wet mud* can be gotten by covering them first with a thin layer of dry plaster of Paris, filling up with the watery mixture.

A "sand trap," designed to obtain *quantitative measurements* of the sand in motion on the sea bottom is described by Lüders (92).[13]

NOMENCLATURE

Fields of study.—Richter (3) defines and tabulates the fields of study he comprises under his term "actuopaleontology." His table

[11] With the exception of the two papers on the organization of the institute already referred to above, B4 and 27.

[12] E. Voigt, "Die Lackfilmmethode, ihr Bedeutung und Anwendung in der Palaeontologie, Sedimentpetrographie und Bodenkunde," *Zeitschr. d. Deutsch. Geol. Ges.*, Vol. LXXXVIII (1936), pp. 272–92.

[13] See also K. Lüders, "Unmittelbare Sandwanderungs-Messung auf dem Meeresboden," *Veröff. Inst. f. Meereskunde, N.F., Geogr.-naturw. Reihe*, Heft 24 (1933), pp. 1–55.

corresponds to the last three sections under the heading, "Modern Marine Life," in this paper (pp. 741–47).

Objects of study.—Four papers (53, 58, 94, 95) give definitions and alphabetical lists of *oceanographic and maritime* terms that are used in geologic studies of marine sediments and conditions of sedimentation. They aim at uniformity of usage and are useful to anyone working in this field.

In an elaborate discussion, Krejci-Graf gives a table (52) in which he defines a large number of terms applied to *surface markings*, such as trails, "hieroglyphs," "fucoids," etc.

STRATIFICATION AND RATE OF SEDIMENTATION

Lüders (34) discusses the origin of the *stratification* of the sediments on tidal flats. He distinguishes between the coarser storm-flood bedding and the fine lamination of tidal sedimentation. The sediment of the tidal flats is derived almost entirely from the sea, brought in by the ingoing current which is stronger than its opposite. The little-known, so typical channel cross-bedding of the silty muds of the tidal flats results from the migration of the tidal channels (*Priele*),[14] which wipe away on one side the sediments laid down but a short time before, while depositing anew on the other.

Figure 2, reproduced from a paper by Lüders not contained in the numbered series, gives a clear picture of the far-reaching changes to which the tidal sediments are subject in relatively few years. Comparison of larger maps with tidal charts shows that the dominant direction in which the channels shift is that of the resultant of the ebb and flood currents and not that of either one alone. Any single *priel* may even show opposite displacements in short time intervals.[15] Trusheim (17) also gives quantitative data and, like

[14] These features had been described in more general terms and figured by Richter (5, p. 231; 4, pp. 25–26).

[15] K. Lüders, "Über das Wandern der Priele," *Abh. Naturwissenschaftl. Verein., Bremen*, Band XXIX, Hefte 1 and 2 (1934). Other papers containing valuable maps and other quantitative data not contained in the Senckenberg list are: W. Krüger, "Meer und Küste bei Wangeroog und die Kräfte, die auf ihre Gestaltung einwirken," *Zeitschr. f. Bauwesen Jahrg. 1911*, pp. 452–64, 585–610; W. Krüger, "Die Entwickelung der Harlebucht und ihr Einfluss auf die Aussenjade," *Abh. Naturwissenschaftl. Verein. Bremen*, Band XXX (1937), pp. 197–208; H. Schütte, "Die Entstehung und Verlandung der Harle-Bucht," *Abh. Naturwissenschaftl. Verein. Bremen*, Band XXX (1937), pp. 209–37.

Lüders, emphasizes that it is impossible to measure or even estimate the time represented by a given thickness of tidal deposits because of the ceaseless shifting of the *priele*.

Häntzschel (96) gives more detailed descriptions of the fine *lamination* and the coarser structural features of the argillaceous silts (*Schlick*) and fine-grained sands of the tidal flats. In the current discussions on the subject the presence of lamination in deposits on tidal flats is generally not mentioned, a fact pointed out recently

FIG. 1.—Laminated silty mud (*Schlick*) exposed along the side of a tidal channel (*Priel*). Tidal flats off the northern strand at Wi helmshaven, Germany. (All photographs taken during the writer's visit in September, 1937.)

by Kindle.[16] The writer must admit that he himself had not thought of delicate structure patterns, such as Häntzschel figures, as having originated on surfaces which lie above water half the time; nor had he connected small- and large-scale channel cross-bedding, when he saw it in Paleozoic rocks, with the winding channels of tidal flats (Fig. 3). Not until he saw them in the field himself did he realize how many similar fossil occurrences may have come into existence in a similar way. Richter has warned repeatedly that we must not

[16] E. M. Kindle, "The Intertidal Zone of the Wash, England," *Rept. of the Comm. on Sedimentation 1928/29* ("Nat. Res. Council Circ." No. 92 [Washington, 1930]), pp. 5–21.

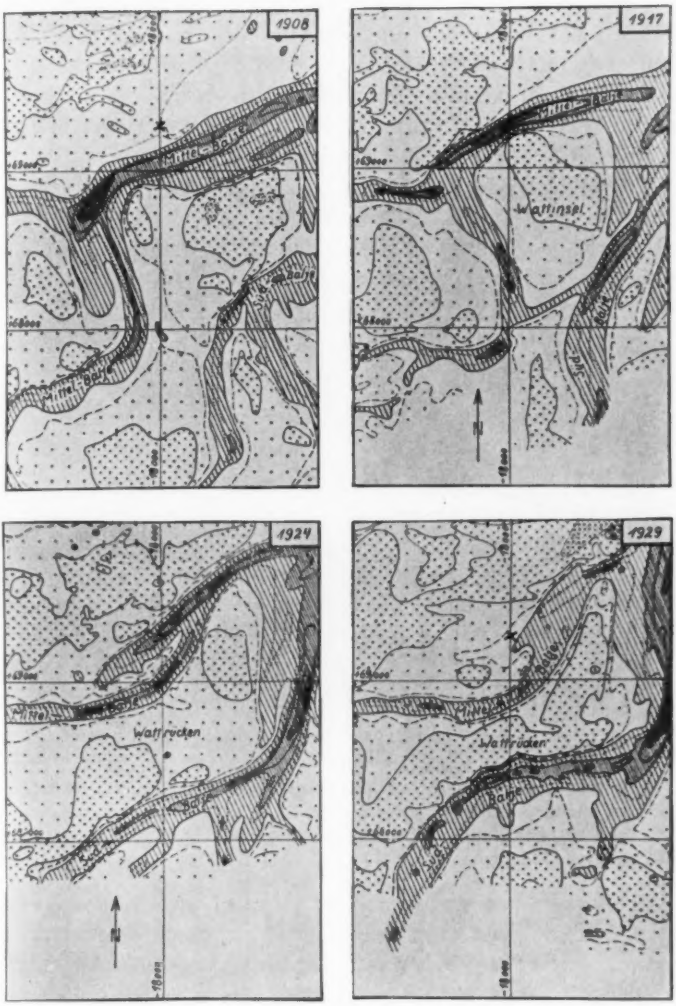

FIG. 2.—Maps of a small area (*ca.* 6 sq. km.) of tidal flats surveyed at intervals of a number of years showing the incessant and irregular shifting of the tidal channels. Contour interval = 0.5 m.; stippled and blank areas above mean sea-level at Wilhelmshaven. (Parts of Plate I of K. Lüders, "Über das Wandern der Priele," *Abh. Naturw. Ver. Bremen*, Vol. XXIX, Nos 1 and 2 (1934.)

assume that, because certain structures occur on tidal flats, they form there only and that the presence of similar structures in rocks proves an origin between low and high tide. Yet it is important that we realize that possibility and correct our thinking accordingly.

CONTEMPORANEOUS EROSION AND INTRAFORMATIONAL CONGLOMERATES

Near the line of mean low water and especially along some of the tidal channels, lateral erosion frequently uncovers older beds. They

FIG. 3.—Small-scale channel cross-bedding exposed along the side of a tidal channel. (For scale note the white *Scrobicularia* shells in the right foreground.) In the distance a Mytilus colony on the surface of the tidal flat. Tidal flats off the northern strand at Wilhelmshaven, Germany.

break away in more or less angular pieces of unconsolidated sediment, exhibiting perfect models of intraformational conglomerates, some as typical flat-pebble conglomerates, others consisting of well-rounded pebbles (Fig. 4). Good illustrations are given by Richter (*f*) and Häntzschel (96). Where such conglomerates cover wide areas in stratigraphic units of limited thickness, as in the Upper Cambrian and lowest Ordovician of the Northern Rocky Mountains, they seem to have formed below the low-water line. That they actually are produced today under such conditions is demonstrated by mud

pebbles, consisting of recent mud, of the sea floor that were brought to the surface in their clayey matrix by means of a clam-shell sampler from a depth of 23 m. (75 ft.), 45 kilometers (28 miles) from the nearest tidal flat (Richter, *k*, *p*.).

RIPPLES

The exceedingly fine clay-silt (*Schlick*) of the tidal flats is generally covered by *oscillation ripples*, which in this fine-grained water-soaked material show broadly rounded crests. They may be per-

FIG. 4.—"Flat-pebble conglomerate" in the making; older tidal silty mud (*Schlick*) suffering erosion through the shifting of a tidal channel. Tidal flats off the northern strand at Wilhelmshaven, Germany.

fectly preserved, as can be seen where older ripples reappear beneath later layers when "contemporaneous" erosion uncovers them (Trusheim, 14).

Where a thin film of water (an inch or less) remains covering the ripples, the surface drift caused by the wind changes them into irregular lines of rounded flat-topped blobs not unlike tar creeping on a sloping surface (Richter, 86 and esp. 93). In the fossil record this has been thought to indicate viscous flow of sediment on relatively steep slopes on the sides of geosynclines. The writer was fortunate in being able to see them himself in all stages of formation on the tidal flat along the Nord Strand at Wilhelmshaven (Fig. 5).

Other more obvious changes, produced by rain and wind, are figured by Trusheim (90), who also gives beautiful pictures of *rhomboid ripples* (83) such as form abundantly and inevitably on every beach (and wherever a thin sheet of rainwater spreads mud over a cement walk!).

Lüders' paper on *giant ripples* (24) is an important contribution, containing quantitative data on current velocities (obtained in

FIG. 5.—"Flow marks" in process of formation through the action of wind on the ripple-marked surface of a sandy tidal flat beneath a thin sheet of water. (Photographed through the water.) Note pencil serving as scale. Tidal flats off the northern strand at Wilhelmshaven, Germany.

field and laboratory) and on the concentration of shells on the broadly rounded crests. Richter (*o*) compares giant ripples ("meta-ripples")[17] of the modern tidal flats with fossil forms ("para-ripples") from the Cretaceous of Saxony.

OTHER INORGANIC MARKINGS ON THE SURFACE OF TIDAL FLATS

The most significant of these are the *ice crystals* of which Häntzschel (81) figures a number of types, all observed on tidal flats with sea water of normal salinity. He also discusses fossil occurrences.

[17] Bucher's terminology (*Amer. Jour. Sci.*, Vol. XLVII, No. 4 [1919], pp. 149–210, 241–69; 15 figs.).

That *mud cracks* are not rare on tidal flats even in the wet climate of the North Sea coast is worth knowing (Trusheim, 8). Schwarz contributes a general discussion of the mechanics of mud-cracking (61).

Two kinds of markings are also described that may well be found in the fossil record, since they are more substantial than the delicate swash marks which have been found so well preserved in early sedi-

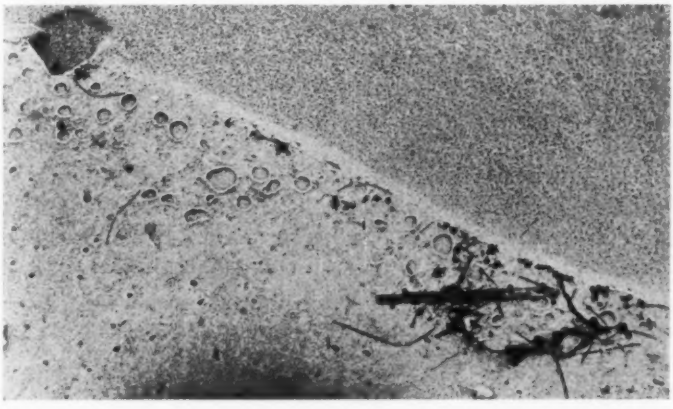

FIG. 6.—Swash mark lined with coarse foam bubbles. (Use impression of heel for scale.) Sandy strand at north shore of island Norderney, Germany.

ments: (1) the honeycomb pattern of *wave foam* left on the sand (80) (Fig. 6) and (2) concentric circles ("swish marks") produced by perishable objects rotated about an axis by the waves (79; *q*, Pl. 20).

CLAY-SILT AND CLAY GALLS

Mechanical analyses and microscopic studies of the typical *clay-silt* (*Schlick*) of the tidal flats, which will make possible a comparison with fossil sediments, are in progress at the institute. Trusheim (13) emphasizes the role diatoms play through the slime they secrete during lifetime and through the addition of their shells to the sediment after death. Schwarz denies that flocculation of river-born muds in the sea water is a factor in the formation of the tidal clay-silt (25).

Richter (*p*) gives concrete illustrations of clay galls in sandy sediments as the result of contemporaneous erosion of older layers of tidal deposits. Eberle (31) describes thin, angular patches of clay-silt which have been lifted and carried onto the sand along a beach by ground ice, objects that would be most puzzling in the fossil record. Paper-like "skins" form when films of diatoms dry and are rolled into oblong bodies several inches long. They pile up on occasions in large numbers in the wave-born shore drift (Trusheim, 13, 88). They would be mistaken for remains of larger organisms when found fossil (cf., e.g., *Corycium enigmaticum* Sederholm of the Bottnische Schieferformation, of Fennoscandia).

SEDIMENTS OF DEEPER WATERS

At the institute systematic studies on the sediments below the low-water line[18] have only begun. Richter (2) gives a list of the locations of samples obtained on a cruise with very brief comments on some of the more interesting samples. Detailed analyses are under way (mechanical, biological, pollen) of samples from a series of drill holes brought down to a depth of 40 m. (131) below the surface of the sediment in water 6–7 feet deep at low tide. Lüders' results of studies with the clam-shell sampler (24) and with his "sand trap" (92) have been quoted above.

[18] Of more recent studies concerning the *sediments* of the North Sea, the following may be mentioned: E. Küppers, "Physikalische und mineralogisch-geologische Untersuchung von Bodenproben aus Nord-und Ostsee," *Wissenschaftl. Meeresuntersuchungen, N.F., Abt. Kiel*, Band X (1906), pp. 3–11; C. Apstein, "Bodenuntersuchungen in Ost- und Nordsee," *Sitzungsber. Ges. Naturforsch. Freunde Berlin* (1916), pp. 355–76; J. O. Borley, "The Marine Deposits of the Southern North-Sea," *Fishery Investigations*, Band IV, No. 6 (2d ser., 1923) (very instructive!); Otto Pratje, "Die Sedimente der deutschen Bucht," *Wissenschaftl. Meeresuntersuchungen, N.F., Abt. Helgoland*, Band XVIII, Abh. 6 (Oldenburg, 1931) (126 pp., 14 pls.); Joh. van Veen, *Onderzoekingen in de Hoofden* ('s Gravenhage; Algemeene Landsdrukkerij, 1936) (252 pp., many maps and illustrations; English and French summaries; bibliography of 212 titles); J. A. Baak, *Regional Petrology of the Southern North Sea* (Wageningen, Holland: H. Veenman & Zonen, 1936). For *biologic* surveys see C. G. J. Petersen and P. Boysen Jensen, "The Valuation of the Sea. I. The Animal Life of the Sea Bottom: Its Food and Quantity," *Rept. Dan. Biol. Stat.*, Vol. XXII (1914); C. G. J. Petersen, "The Animal Communities of the Sea Bottom," *ibid.*, Vol. XXI (1913); H. M. Thamdrup, "Beiträge zur Oekologie der Wattenfauna," *Meddelelser fra Kommissionen for Danmarks Fiskeri og Havundersogelser Serie, Fiskeri*, Vol. X, No. 2 (1935) (beautifully illustrated).

BEACH SANDS, BEACH CUSPS, AND DUNES

Thin bands of titaniferous *black sands* are described by Trusheim (77); *beach cusps* (*Strandhörner*) by Gellert (98).

The *rate of advance* of a *migrating dune* was obtained by Overbeck (15) in a simple and interesting way. He found heather in bloom covered by the advancing dune. Only after digging back 1.70 m. (5.6 ft.) did he reach heather that had not started to bloom this year. The date on which heather started to bloom at that locality—the barrier-beach portion of the island of Sylt—could be secured within narrow limits, showing that the dune had here advanced 1.70 m. in not more than seven weeks.

The *plant associations* of a miniature island which is at present being built up without the aid of man in the midst of large tidal flats are described and mapped by Leopold (65).

1*a*. QUATERNARY STRATIGRAPHY AND HISTORY OF THE GERMAN NORTH SEA COAST, INCLUDING MODERN COASTAL ENGINEERING PROBLEMS

On the floor of the North Sea (Dogger Bank, Helgoland, etc.) at depths below 50 m., fresh-water sediments, including peat deposits, are found. Others overlie marine beds near the coast and are themselves covered by the modern tidal clay-silt and sands to a depth of many feet. Complicated changes in the position of the strand-line are thus indicated all along the coasts of the North Sea, extending back into the earlier Pleistocene and continuing at present, with the man-induced changes in the shape and position of the barrier-beach islands, as one of many factors. If actual sinking is going on at the present at an appreciable rate, it will influence the complicated operations by which an attempt is made to control the positions of the channels for purposes of navigation. While these matters are, of course, purely European in scope, they involve methods of study and of reasoning that apply to our own problems. Readers interested in an exposition of the lines of attack on this problem followed in this particular part of the North Sea shore are referred to a monograph by Schütte.[19]

[19] Heinrich Schütte, *Das Alluvium des Jade-Weser Gebiets: Ein Beitrag zur Geologie der deutschen Nordsee Marschen* (Oldenburg: Gerhard Stalling, 1935); 2 vols., one text; the other maps, sections, illustrations.

Six of the numbered series of publications contain detailed observations and controversial matters (Schütte, 30, 70; Hecht, 37; Schwarz, 53, 56, 69).

These papers deal with *pollen analysis* as an essential tool in these studies. Thus Firbas (1) could show that the peat which outcrops 5–6 m. below mean low water at Helgoland must be of interglacial and not, as had been assumed, of postglacial age, for pollen of spruce—a tree which never reached northwestern Germany in postglacial time, since it required a more continental type of climate than has prevailed since the last advance of the glaciers—dominate the flora in the upper layers.

The general scope of pollen-analytical studies is outlined by Overbeck (5), who also gives a map and list (28) of the large number of peat samples being studied under his direction.

Häntzschel (100) gives a well-illustrated account of the methods that are being used to accelerate the deposition of tidal sediments in the efforts to wrest more land from the sea.

II. MODERN MARINE LIFE

METHODS OF STUDY

Schwarz (33) describes the mounting of aquaria for easy handling in use at the institute.

HABITS AND FOOD

A few short papers record casual observations concerning food habits: Schwarz (62) on the indigestible parts (*Gewölle*) disgorged by gulls—especially quantities of shell fragments which may accumulate in considerable quantities beyond their normal range of deposition; Wachs (40) and Linke (87), evidence that sea birds occasionally feed on *Balanus*, leaving characteristic scars in dense colonies; pictorial evidence of the excessive voracity of the cod (Meyer, 45).

An important laboratory investigation was conducted by Hecht (57) on the degree to which *polychaete worms* can stand *reduction of oxygen* content in the sediment in which they live and burrow. He found that such forms as *Arenicola* and *Nereis* can live without damage with oxygen reduced to 10 per cent of its normal quantity. They can even live for a week without any oxygen, deriving oxygen from

the glycogen of their bodies. They lived in the aquarium in sediment that was black to the surface, provided only oxygen reached them at intervals. This explains the presence of bore holes in black shales, where they may even be abundant.

TRAILS, BURROWS, AND FECAL REMAINS ("ICHNOLOGY")

Such humble traces are often the only record of life in sediments of the past, or they are at least the only evidence we have that large groups of organisms have existed at the time certain sediments were formed. Their correct interpretation is an essential task of paleontology if it is to read correctly the geological record. Even if no larger problems were linked with them at all, every geologist working in sediments welcomes information about them simply because he meets them so frequently in his work and is puzzled by them. The only way to get a satisfactory understanding of this type of fossils is to study their counterparts as they are seen on the muds and sands of the modern tidal flats. They have been recognized from the beginning as important objects of study at the institute.

Richter (93) contributes a valuable discussion of the peculiar fact that we find so frequently *burrows of marine invertebrates in well-laminated sediments*. Should one not expect the burrowing action to destroy the lamination, if it is true that all the mud of tidal flats passes in twenty-two days through the intestinal track of mud-eaters? The answer is readily seen on modern tidal flats; the muds and sands are constantly worked over by the currents, washed away, and redeposited. The newly formed laminated sediments are invaded by a new set of burrowers. The fossil record, as always, is only a last short event preserved by chance out of a long series of erosions and depositions.

The common trails and burrows of the tidal flats of the North Sea[20] are described and figured in several papers by Richter (*g*, *q*).

A number of *star-shaped impressions* are described. Häntzschel (76) shows that the one most common on the tidal flats is produced by the pelecypod *Scrobicularia plana* (Da Costa), which extends its intake siphon in different directions, "pipetting" off the nourishing surface layer. Less regular star patterns, sometimes with bifurcating

[20] See especially also the paper by Thamdrup (*op. cit.*).

rays, are produced by *Nereis* when it extends its head and body from the burrow onto the surface. Very small and delicate stars are fashioned on the surface by the small amphipod *Corophium* (Trusheim, 35), which lives in countless numbers in delicate burrows which frequently have U-shape (*q*). All three may be seen on any trip onto the tidal flats. It is more surprising to find a small fish (*Cobius*) producing a star pattern as it covers a pelecypod valve with sand beneath which are hidden its eggs (Häntzschel, 84).

A remarkable observation is reported by Richter (*n*), who saw perfect impressions made by living flounders (*Pleuronectidae*) which had rested on the sand and had swum away when the tide dropped low, without marring the sharpness of the impression they left, which was like that of a dead fish.

Linear trails consisting of regular repetitions of lines, remotely suggesting *Climactichnites*, are produced, under suitable circumstances, by bottom-dwelling flat fish (Wachs, 32). Trusheim (49) figures tracks of an *Apus*, which are interesting because of points of resemblance with trilobite tracks. Linke (89) gives evidence that drying-out may alter considerably the appearance of common trails.

Misleading impressions which would puzzle us in the fossil record are figured, like flat depressions in the sand made by gulls (Sivers, 10) or apparently five-toed tracks made by three-toed birds (Trusheim, 11).

DEATH AND MODE OF PLACEMENT IN SEDIMENT

Causes of death.—Mass deaths of fishes and lower forms of life, due to poisonous substances from *sapropel bottoms*, stirred up by storms or other agencies, are described by Eberle (12) and Meyer (63). Eberle counted 86 carcasses of herring and flounder in 50 square meters of shore drift, and 400 out in the water over an area of about 600 square meters. In the faint depressions which are so characteristic on all tidal mud surfaces, two bodies are likely to become lodged close together, a condition commonly observed in the fossil record.

A case of large numbers of eel killed by a *disease* brought about by a bacillus resembling that which causes cholera is reported by Meyer (68). Along 1 km. of shoreline he counted 1,200 large one-pound eels which had been washed ashore in one night. Such epidemics tend to break out in shallow water on warm summer nights.

When fish die in such numbers, *fish scales* may make up a large part of the drift on shores where few or no dead fish get stranded (Eberle, 12; Linke, *Natur und Volk* [1935], pp. 128–29).

Transportation and accumulation.—At times of exceptionally low tides, *insects* fly out onto the tidal flats in vast numbers. Sudden off-shore winds destroy them. The shore drift in such cases may consist largely of winged insects. Trusheim (9) estimated forty million beetles in a stretch of shore drift 1.5 km. long. Details of such wholesale burial of insects in the sea are given by Schwarz (46), together with a list of identified forms by Franz (47).

The larger *jelly fish*, where stranded along sandy shores, leave a perfect impression of the underside of their bodies. Their slowly shrinking bodies protect the sand they cover from the action of the wind and thus tend ultimately to leave the impressions of their bodies slightly above the surface of the sediment, a condition familiar in such fossil cases as those of the Cambrian of Alabama (Brooksella etc.). This process which may be observed on almost any sandy shore, is described and well illustrated by Trusheim (41). On the clay-silt of the tidal flats of the vicinity of Wilhelmshaven the writer had a chance to see delicate, smooth but sharply defined, penny-size impressions made by the bodies of a *hydromedusa*, whose body is quickly reduced to a mere film. They have recently been described by Häntzschel (97). Such records should exist in fossil sediments.

After heavy storms all the forms which live in large numbers in shallow water are, of course, likely to appear in large quantities in the shore drift. Trusheim (41) figures, for instance, such chance accumulations of the beautiful and delicate tubes made of neatly cemented sand grains by the polychaete *Lagis koreni* of which 150–200 have been found inhabiting $\frac{1}{10}$ square meter; and of the flexible, slender tubes of *Lanice conchilega* loosely covered with cemented shell fragments. Up to 389 individuals of the latter form have been observed living on an area of a square decimeter.

Large quantities of shells of forms that live in shallow water are washed ashore now and then in numbers that surprise those who are not familiar with the crowding of life in the nourishing muds of shallow waters. Specimens of *Cardium edule* have been found, for instance, living as many as 2,080 beneath a square meter of surface. Of the echinoid *Echinocardium cordatum* over 200 have been found

in a cubic meter of sediment in water 15 m. deep (Häntzschel, 91). Both forms may be washed ashore in enormous numbers. The delicate spines of *Echinocardium* are found all through the sands and silts and may even accumulate in layers of which they form the chief, closely knitted constituents (Schwarz, 38), paralleling familiar fossil examples.

Vast numbers of *exuviae* (shed skins) of shrimps (*Crangon*) may be thrown ashore in almost solid lines of drift (Schwarz, 66). They may have drifted considerable distances—a warning to the geologist not to be too ready to assume that the fossils he finds lie where they lived. A grotesque illustration of this point is the belt of marine shore drift crowded with the bodies of *earthworms* which Lüders (20) describes, the result of an exceptional flood tide which rose fully 2 m. above the normal high-water level.

A small gastropod, *Hydrobia*, lives on the fine, sticky mud of the near-shore zone of the tidal flats in countless numbers (800–1,000 per square meter) and covers it with its curly-cue tracks. The empty shells float easily and accumulate along the shore in vast quantities. As shells of the same genus fill many beds in the Tertiary of the Rhine Valley, three instructive papers (Ankel, 6; Schwarz, 7; Trusheim, 8) are devoted to them, giving detailed observations on their mode of living and contrasting the conditions of sedimentation in the Aquitanian sediments with those of the present-day tidal flats.

When one scoops up a shovel-full of *Hydrobia* shells along the shore, one is struck by the complete absence of the horny *opercula* of which there should be one for every shell. The two seem to be handled separately by the sea. A case of innumerable opercula of another gastropod common along the shore, *Littorina*, forming a line of drift along the edge of the water without a single shell, is mentioned by Trusheim (44) in connection with the description of an interglacial deposit that is rich in opercula of *Bythinia tentaculata* (30–50 opercula per square decimeter). Similar deposits are known in the geologic record, such as the bed in the Etchegoin formation that serves as a key bed to Californian oil geologists.

Modes of placement in sediment.—The position of fossils in a sediment is determined by the mechanical forces that act at the time

it reaches its final resting-place. Striking cases are, e.g., the parallel orientation of graptolite rhabdosomes in the Ordovician of New York or of turreted gastropod shells like *Turritella* in the Tertiary of Texas; or the "pavements" of pelecypod shells, all with their convex sides turned up, common in many formations; or the shingle-like packing of shells, as, e.g., of *Rafinesquina* in the Upper Ordovician of the Cincinnati region, or of *Pecten* in the Tertiary of California; or the vertical position of elongated shells in a sediment, as in the surprising case of *Orthoceras* shells described from the Oneonta sandstone of New York. The act of placing shells in a definite position with reference to the sediment is called *Einregelung* in recent German literature.

Good observations on the position of modern and fossil shells and carapaces within the sediment are contained in one of Richter's papers (*c*). The curious case in which the right and left valves of a pelecypod are separated by currents and deposited at different places is described and discussed in another (*d*).

Systematic *experiments* were made by Trusheim (42) in the hydrological laboratory. The odd case of turreted gastropod shells (*Cerithium*) found in *vertical position* in Tertiary sediments is discussed in two papers (Klingner, Schwarz, 50; Krejci-Graf, 60).

Below a given point on the surface, different associations of burrowing animals live at different depths, introducing within a depth of some 3 feet what in the fossil record we might describe as a "change of fauna," but which has actually nothing to do with a change. Actual changes are brought about regularly through the natural succession of animals in a given environment, as when oyster beds are smothered by the spreading of tubicole worms such as *Sabellaria*, which in turn may succumb to byssus-weaving pelecypods like *Mytilus*. These and related matters are discussed by Richter (*e*).

Chemical and physical changes in the carcass.—Hecht's paper (71) on the changes in the organic parts of animals after death deserves special attention. Carcasses were studied at intervals, buried on the sediments of the tidal flats or in aquaria. An important object of study was, for instance, the body of a shark which surveyors had found stranded in 1924 near the outer edge of the largest tidal flat.

They had buried it beneath 1 m. of sand. Two years later they located it again and found that it had not changed noticeably (*m*). It was partly uncovered and studied in 1926 and again in 1931. Attempts were made to check the findings in the field against parallel observations in the laboratory (aquaria).

Information was sought on two basic questions: (1) the *chemical nature* of the products of decomposition, especially that of *end products* that might become incorporated in the sediment to serve ultimately as source materials for petroleum, and (2) the *rate of decomposition* with a view to shedding light on the conditions of fossilization.

For the concrete observations and determinations which constitute the essential body of such a report, the reader is referred to the original. Of general conclusions, a few are here listed: (1) The albuminous substances decompose so much faster than the fatty constituents that they may not be expected generally to furnish end products that become a part of the sediment. (2) The end product of retarded decomposition is a homogeneous solid substance different from adipocere (*Leichenwachs*).[21] (3) The more rapid escape of nitrogen accounts for the ratios of C:N greater than any known in living bodies, such as were found in many cases by Trask (Hecht, 72). (4) The solid residual substances (*Urbitumen*), like all sediment in shallow water, pass and repass through the intestines of mud-eaters and become part of the fecal materials which constitute the bulk of such fine muds. This treatment plays an important role in the preparation of the source materials for petroleum.[22] (5) The CO_2 product in the course of decomposition exerts a solvent action on shells and bones. (6) Fatty substances may pass into the enveloping sediment and cement it, concretion-like. (The sand on top of the above-mentioned shark was found cemented in this fashion; the lower side was never exposed.)

Weiler (16) reports observations on the bodies of dead *fishes*

[21] This is challenged by Wasmund, who reports many cases of adipocere from bodies that lay in sea water (Erich Wasmund, "Die Bildung von anabituminösem Leichenwachs unter Wasser," *Erdölmuttersubstanz*, Heft 10 [Stuttgart, 1935], pp. 1–70, esp. pp. 55–59).

[22] This conclusion is also challenged by Wasmund.

which shed light on a number of fossil cases. The peculiar curving which is so often seen in fossil fishes occurs inevitably whenever slender fish with weak skeletons decompose. The curving may rupture the body and actually sever the head completely. Differential transportation may in such cases lead to a local accumulation of fish heads at one place and headless bodies at another. The paper includes illustrations and discussion of fossil occurrences.

BIOFACIES

The environmental factors in the association of organisms ("*bionomics*").—Studies of purely biological character have not been pursued to any extent so far at the institute. Hecht and Matern's study of the ecology of *Cardium* (39) and Trusheim's observations on colonies of *Balanus* and *Mytilus* (54) may be mentioned here; also, Schwarz's (67) on phototropic behavior of many common forms of the tidal flats.[23]

Brockmann (29*a*) objects to the assumption which prevails among geologists that the brackish-water zone around the mouths of large rivers is a zone of wholesale destruction of life, especially plankton. He points out that for the chief forms it is just the opposite—a region of tremendous development of the plankton. Meyer's paper (59) deals with the distribution of one species.

III. INTERPRETATION OF FOSSIL SEDIMENTS

INTERPRETATION OF SPECIFIC STRATIGRAPHIC UNITS

Richter's analysis of the dark-colored Devonian *Hunsrückschiefer*, famous for its remarkable pyritized echinoderms (Bundenbach), is a model in method and results. Three parts have appeared so far. The first (51) analyzes the probable depth of the sea and especially the possible reasons for the unusual composition of the fauna, which is the inverse of that normally found—echinoderms common, shelled forms rare. He considers three possible reasons: (1) *environmental selection:* peculiar ecologic conditions (as, e.g., in the *Echinocardium filiformis* facies of the North Sea fauna which comprises

[23] Control experiments seem needed here. The writer saw, e.g., in company of Dr. Häntzschel, numerous *Littorinas* crawling in nearly parallel directions, as their long trails showed, but *not* toward the sun as Schwarz reports.

68 echinoderms against 26 species of other invertebrates); (2) *mechancial selection:* differential transportation of the organic remains by currents; and (3) *diagenetic selection:* removal of some types of shells by essentially contemporaneous solution. He concludes that (1) and (3) are involved in the Hunsrückschiefer.

The second paper (86) discusses the origin of some of the markings seen on the bedding planes, especially those which had formerly been attributed to slumping of the sediment on unusually steep slopes thought to have been characteristic of geosynclines (cf. p. 735 of this paper). The last paper (93) contains the discussion of the relation of lamination to the burrowing activity of organisms mentioned on page 741. It is applied to the fossil case in hand.

Characteristic cross-bedding and surface markings which originate only in shallow water are described by Häntzschel (82) from the Nama-Transvaal system of South Africa and compared with their modern counterparts on the tidal flats.

INTERPRETATION OF "PROBLEMATICA"

A preliminary classification of trails, tubes, and burrows generally ascribed to worms is given by Richter (*s*) with good illustrations and comparisons. His important studies on *Sabellaria*, *Scolithus*, and allied forms are contained in three papers (*a*, *b*, and especially *r*). Specific forms are discussed in other papers, as, e.g., "Arenicoloides" (*g*); meandering traces, especially the *helminthoids* (*i*, *t*); undersides of layers covered with a maze of interwoven "trails" (*Ceflechtquarzite*) (*b*, *h*); *Corophoides* (*l*); etc.

Trusheim (73) identifies surface markings characteristic of modern tidal flats on bedding planes of the Triassic Muschelkalk. Häntzschel figures and discusses markings on sandstones from the Cretaceous of Saxony, some star-shaped (36, 78), others spiral (75).

ORIGIN OF SPECIFIC ROCK TYPES

Two papers by Schwarz deal with the origin of the *flints* in the European chalk (18, 26). The second paper also contains a discussion of *radiolarites*, based on important studies made with a peculiar technique, published elsewhere.[24]

[24] A Schwarz, "Die Natur des culmischen Kieselschiefers," *Abh. Senckenb. Naturf. Ges.*, Band XLI (1928).

Reuling's paper (74) consists of an attempt to interpret in a novel way the dolomite content of the Funafuti bore record. The peculiarities in the distribution of dolomite in the bore hole to which he calls attention seem significant and demand an explanation, though the writer doubts if Reuling's interpretation solves the problem it presents.

IV. INTERPRETATION OF FOSSIL MARINE LIFE (PALEOBIOLOGY)

Richter's elaborate paper (19) on the relation between function and form in the calyces of the lid-bearing corals of the Paleozoic (*Calceola*, *Coniophyllum*, etc.) may well serve as a model for paleobiological reasoning applied to invertebrates, which starts with the facts of the fossil remains and reasons back, attempting to restore the functioning of their parts in life.

APPENDIX A

PAPERS BY RUDOLF RICHTER DIRECTLY RELATED TO THE PURPOSES OF THE INSTITUTE, PUBLISHED PRIOR TO ITS FOUNDATION

Numbered series: "Flachseebeobachtungen zur Palaeontologie und Geologie":

a) I.* "Ein devonischer Pfeifenquarzit," *Senckenbergiana*, Vol. II (1920), pp. 215–35.

b) II.* Scolithus, Sabellarifex und Geflechtquarzit," *ibid.*, Vol. III (1921), pp. 49–52.

c) III. "Die Lage schüsselförmiger Körper bei der Einbettung," *ibid.*, Vol. IV (1922), pp. 105–26.

d) IV. "Gesonderte Verbreitung der rechten und linken Klappe einer Muschelart," *ibid.*, pp. 127–32.

e) V. "In sich bedingter Faunenwechsel," *ibid.*, pp. 133–37.

f) VI. "Ton als Geröll im gleichzeitigen Sediment," *ibid.*, pp. 137–38.

g) VII. "Arenicola von heute und 'Arenicoloides,' eine Rhizocorallide des Buntsandsteins, als Vertreter verschiedener Lebensweisen," *ibid.*, Vol. VI (1924), pp. 119–40.

h) VIII. " 'Geflechtquarzite' aus einzelnen Vertikalröhren nachträglich zusammengeballt," *ibid.*, pp. 140–41.

i) IX. "Zur Deutung rezenter und fossiler Maeander," *ibid.*, pp. 141–57 (Figuren).

* Number does not appear in title; given afterward.

j) X. "Weiteres zur verschieden-Häufigkeit der beiden Klappen einer Spezies bei Muscheln und Brachiopoden," *ibid.*, pp. 157–63.

k) XI. "Schlickgerölle, auf dem Meeresgrund entstehend," *ibid.*, pp. 163–64.

l) XII. "Bau, Begriff, und palaeogeographische Bedeutung von Corophioides luniformis (Blanckenhorn, 1917)," *ibid.*, Vol. VIII (1926), pp. 200–219.

m) XIII. "Verzögerte Verwesung im meerischen Grundwasser," *ibid.*, pp. 219–21.

n) XIV. "Abdrücke lebendiger Tiere (Fische und Würmer)," *ibid.*, pp. 221–24.

o) XV. "Die Grossrippeln unter Gezeitenströmungen im Wattenmeer und die Rippeln im Pirnaer Turon," *ibid.*, pp. 297–305.

p) XVI. "Die Entstehung von Tongeröllen und Tongallen unter Wasser," *ibid.*, pp. 305–15.

Papers without numbering:

q) "Eine geologische Exkursion in das Wattenmeer," *Natur und Museum*, Vol. LVI ("Bericht der Senckenbergischen Naturforschenden Gesellschaft" [Frankfurt a.M., 1926]), pp. 289–307.

r) "'Sandkorallen'-Riffe in der Nordsee," *ibid.*, Vol. LVII (1927), pp. 49–62.

s) "Die fossilen Fährten und Bauten der Würmer, ein Überblick über ihre biologischen Grundformen und deren geologische Bedeutung," *Palaeontologische Zeitschrift*, Vol. IX (1927), pp. 195–240.

t) "Psychische Reaktionen fossiler Tiere," *Palaeobiologica*, Vol. I (1928), pp. 225–44.

APPENDIX B

All the papers of this list were printed in publications of the Senckenbergische Naturforschende Gesellschaft, Frankfurt am Main. The following abbreviations are used for the titles of the different series of publications: *Abh.—Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft; S—Senckenbergiana; NuM—Natur und Museum; NuV—Natur und Volk* (continuation of *Natur und Museum* under new title).

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2. RICHTER, EMMA. "Liste der Grundproben von der Studienfahrt der 'Minseroog,' 1923," *S*, Vol. X (1928), pp. 195–203.
3. RICHTER, RUDOLF. "Aktuopalaontologie und Paläobiologie, eine Abgrenzung," *S*, Vol. X (1928), pp. 285–92.
4. ———. "Gründung und Aufgaben der Forschungsstelle für Meeresgeologie 'Senckenberg' in Wilhelmshaven," *NuM*, Vol. LIX, Heft 1 (1929), pp. 1–30.

5. Overbeck, Fritz. "Aufgaben und Ziele des Botanikers bei der Erforschung der Doggerbank," *NuM*, Vol. LIX, Heft 1 (1929), pp. 30–33.
6. Ankel, Wulf Emmo. "Hydrobienschill und Hydrobienkalk," *NuM*, Vol. LIX, Heft 1 (1929), pp. 33–49.
7. Schwarz, Albert. "Die Ausbreitungsmöglichkeiten der Hydrobien (Die Bildung eines einheitlichen Hydrobien-Sedimentes)," *NuM*, Vol. LIX, Heft 1 (1929), pp. 50–51.
8. Trusheim, F. "Trockenrisse mit Hydrobienfüllung im Schlickwatt," *NuM*, Vol. LIX, Heft 1 (1929), pp. 52–54.
9. ———. "Massentod von Insekten," *ibid.*, pp. 54–61.
10. Sivers, Wolfgang von. "Irreführende Spuren von Möwen," *NuM*, Vol. LIX, Heft 1 (1929), pp. 62–63.
11. Trusheim, F. "Fünfzehige Vogelfährten," *NuM*, Vol. LIX, Heft 1 (1929), pp. 63–64.
12. Eberle, Georg. "Ein Massensterben von Heringen," *NuM*, Vol. LIX, Heft 1 (1929), pp. 64–70.
13. Trusheim, F. "Eigenartige Entstehung von Tongallen," *NuM*, Vol. LIX, Heft 1 (1929), pp. 70–72.
14. ———. "Rippeln in Schlick," *ibid.*, pp. 72–79.
15. Overbeck, Fritz. "Wanderdünen und Pflanzenwuchs," *NuM*, Vol. LIX, Heft 1 (1929), pp. 79–80.
16. Weiler, W. "Über das Vorkommen isolierter Köpfe bei fossilen Clupeiden," *S*, Vol. XI (1929), pp. 40–47.
17. Trusheim, F. "Zur Bildungsgeschwindigkeit geschichteter Sedimente im Wattenmeer, besonders solcher mit schräger Parallelschichtung," *S*, Vol. XI (1929), pp. 47–55.
18. Schwarz, Albert. "Zur Bildung der Feuersteine," *S*, Vol. XI (1929), pp. 56–57.
19. Richter, Rudolf. "Das Verhältnis von Funktion und Form bei den Deckelkorallen," *S*. Vol. XI (1929), pp. 57–94.
20. Lüders, K. "Spülsaum aus Regenwürmern," *NuM*, Vol. LIX, Heft 3 (1929), pp. 174–75.
21. Dunk, von der. "Perlschnüre und Knopfreihen als Oberflächenformen eines Sandstrandes unter der Einwirkung des Windes," *NuM*, Vol. LIX, Heft 4 (1929), pp. 197–99.
22. Eberle, Georg. "Ein einfaches Mittel um Tierspuren zu erhalten," *NuM*, Vol. LIX, Heft 4 (1929), pp. 200–204.
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26. ———. "Untersuchungen über die Bildungsweise von sedimentären, festen Kieselsäuregesteinen nichtklastischen Ursprungs," *ibid.*, pp. 159–92.
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86. RICHTER, RUDOLF. "Marken und Spuren im Hunsrück-Schiefer. 1. Gefliess-Marken," *S*, Vol. XVII (1935), pp. 244–63.
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PRIMORDIAL SEGREGATION OF METALS

J. S. DE LURY
University of Manitoba

ABSTRACT

Unevenness of geographical distribution of metals and abundant evidences of fortuity of association of igneous rock and ore are considered to be anomalous under the theory of magmatic differentiation, which is commonly extrapolated to imply that compositionally diverse igneous rocks and, presumably, their affiliated metalliferous deposits were derived during geologic time from a universal type of homogeneous parental magma. Recent deductions from the constancy of atomic weights of ore lead of all ages and the variability of rock leads are similarly disturbing to current metallogenic theory. A hypothesis of primordial differentiation of earth material with a consequent primitive segregation of metals is outlined, which seems to remove the anomalies shown by metal distribution and association and to explain the evidence from lead atomic weights.

INTRODUCTION

The view goes almost unchallenged that most ore deposits of magmatic origin were derived by differentiation from the same parental magma that gave rise to contemporaneous and associated igneous rocks. The possible concept that the successive primary magmas of the geologic record may have had a variety of compositions as a consequence of derivation in an originally heterogeneous earth is currently overshadowed by a view which was concisely stated by Daly: "With Bowen, and now Harker, Smyth, and others, we may agree that the only post-Cambrian primary magma has been basic and the author regards it as dominantly basaltic."[1] If this concept is expanded to embrace current metallogenic theory, it is apparent that the same basic type of universal magma must be accepted as the source of the metals.

Certain weaknesses of this widely extrapolated differentiation hypothesis for the mass production of diverse igneous products during geologic time were recently pointed out, and it was suggested that rock diversification might have been largely primordial.[2] No

[1] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill, 1933), p. 332.

[2] J. S. De Lury, "Heterogeneity of Parent Magma," *Jour. Geol.*, Vol. XLV (1937), pp. 381–90; "Diversification of Igneous Rocks," *Contributions to Canadian Mineralogy* (Toronto University Press, 1937), pp. 83–94.

conclusions bearing on metallogenesis were made at the time, though it was apparent that ore deposits offer similar difficulties to the theory of local differentiation. Moreover, the concept of a major primordial differentiation remains to be tested in the light of rock and metal association.

To be effective, the commonly accepted processes of differentiation must follow a fairly precise course, and their operation on each of a geologic succession of primary magmas of similar composition is expected to lead to considerable uniformity of effects. It is apparent, however, that assemblages of igneous rocks are vastly different from place to place. There is much unanimity in ascribing diverse members of a group to differentiation from a common magma, but little agreement concerning the chain of processes involved. Similarly with ore deposits: economic geologists accept differentiation as the explanation of many ores, but do not agree on the manner, the time, or the place of the concentrating processes. Of these uncertainties, perhaps that of time has been the most neglected, and it is this to which the writer will devote attention.

The evidence of the atomic-weight constancy of ore lead of different ages, when viewed in conjunction with current theory concerning the method of metal concentration from magma to ore, suggests that the secular aspect of the problem has been neglected. According to Holmes:

> The proof is complete that ore-lead cannot be a concentration from either granitic or basaltic rocks, or from their respective magmas. . . . . Since ore-lead has no genetic connection with either acid or basic magmas, it must have ascended from a source lying below the granitic and basaltic layers of the lithosphere.[3]

Lead is associated with many other metals in a variety of ore deposits, so that, as pointed out by Holmes, it becomes difficult to retain the commonly held view that metals in general are differentiated locally from parental magma. Before reading the important evidence concerning ore lead and rock lead, the writer had already concluded on entirely different grounds that local and geologic differentiation meets serious difficulties and that a different way out was

[3] Arthur Holmes, "The Origin of Primary Lead Ores," *Econ. Geol.*, Vol. XXXII (1937), pp. 763–81.

apparent. The appearance of the conclusions from lead atomic weights makes the time opportune for naming other objections to current theory and for suggesting a solution.

ANOMALOUS DISTRIBUTION OF METALS AND FORTUITY OF ASSOCIATION OF METAL AND ROCK

The so-called consanguineous assemblages of igneous rocks of diverse composition vary greatly in different regions. Lava varieties and their sequences in various volcanic centers, for instance, do not exhibit the uniformity of effects expected from the operation of the same differentiation processes on a common kind of parental magma. If concentrations of metal are regarded as products of the same course of differentiation, further difficulties arise.

Gold deposits appear, in general, to show a community of origin with granite or similar quartzose rocks. In the expanded theory of differentiation these quartzose rocks are differentiates from a universal type of basic magma, which must accordingly be looked upon as the source of gold. The earth layer supplying the universal parental magma is expected to be fairly uniform in composition and to supply about the same proportion of gold in all instances. A process delicate enough to cause the differentiation of granite from a basic magma should be equally effective in all instances in segregating gold in the acid differentiates. Yet it appears that the granitic cores of the various mountain systems are very unequal in their gold content. In attempting to overcome this difficulty it might be suggested that unequal distribution of gold is apparent rather than real, and that the metal has been deposited equally but in different ways—in some places more concentrated and obvious; and in others more dissipated and, therefore, less in evidence. If this were true, however, gold placers should not reflect the same difference and should be in about equal abundance in different eroded mountain systems. Again it might be offered in explanation that mountain systems have had different erosion histories and that in some instances more than in others placer gold has been dissipated or buried. Such an explanation, however, would not cover the difficulty presented by the relative scarcity of both lode and placer tin. This metal is even more definitely associated with granite intrusions than is gold; yet, notwithstanding the widespread occurrence of granite, tin is pro-

duced in comparatively few regions. There seems to be at least a vague fortuity of occurrence of gold and of tin with granite masses. The tin regions of the world are typically not gold regions, and vice versa, though it is reasonable to expect from the differentiation theory that a region rich in placers of one of these metals should be similarly endowed with the other. Further instances of metals commonly associated with batholithic intrusion could be examined to draw similar conclusions. Why, for example, is the rare element lithium abundantly concentrated in the pegmatites near a few intrusions of granite and is not apparent around the larger number? The whole group of pegmatites offers difficulties. In a swarm of pegmatite bodies, all apparently of the same generation, a few are found to have remarkable concentrations of rare elements, while the larger number appear to be barren. The sum of evidence concerning the distribution of metals in and around batholiths offers much that seems anomalous under current petrogenic and metallogenic theory.

Attention will now be directed to other kinds of intrusive bodies with their associated metals. Diabase is a very common rock of the basalt-gabbro clan and typically appears in dikes or sills. Throughout a wide area tributary to Cobalt, Ontario, diabase of fairly uniform composition occurs intermittently and has as common associates veins containing a rare assemblage of metals, namely, cobalt, silver, nickel, antimony, arsenic, and bismuth. Similar ores are found in very few parts of the world, and there is room for serious wonder—if local and geologic differentiation governs the association of rock and ore—why signs of these metals are not more frequent in association with the common sills and dikes of diabase. The genetic association of the complex ore and diabase is undoubted in the Cobalt region, yet the rock is not an extreme product of differentiation and gives no hint in itself that its parental magma gave rise to the associated metals. This evidence definitely suggests a fortuity of association of rock and metal.

Another of the well-recognized groups of consanguineous rock and metals is illustrated by the association of nickel, copper, and platinum in heavy sulphide ores with gabbro or norite. Gabbro is compositionally about the same rock as diabase and is similarly common, yet relatively few gabbro bodies show any traces of nickel-

ore minerals. This is all the more remarkable since intrusions of this rock are looked to for the best field evidences of processes of differentiation. Associations of nickel and gabbro are common enough to establish community of origin, but are too infrequent to remove the suspicion of a fortuity of association which is not consonant with the broad concepts of magmatic differentiation.

Other examples of metal occurrences could be gathered which would indicate inconsistency with current theory. Every unique ore deposit raises questions. However, enough facts have been given to throw serious doubt on the adequacy of accepted theory. Perhaps the writer is asking too much in the way of uniformity of effects from the differentiation hypothesis. There may well be sufficient differences of environment to account for considerable variations of metal and rock associations in the shallower levels of the earth. On the other hand, so much evidence exists which seems to show that igneous-rock diversification calls for further explanation than is provided by differentiation as a local geologic process that the writer was forced to the hypothesis of primordial differentiation. While the evidence of fortuity of association of metal and igneous rock seems to support the latter hypothesis, it should not be viewed as the sole support.

CONCENTRATION OF METALS BY PRIMORDIAL DIFFERENTIATION

It is assumed that the solid earth was born from a liquid state and that it crystallized in the main from the core outward as deduced by Adams.[4] Supporting this assumption is the sum of evidences indicating a considerable degree of compositional layering in the earth. Seismologic data suggest a shell-like arrangement in the interior, while compositional zoning is indicated by the persistence in time and space of large intrusive and extrusive bodies of igneous rock of fairly uniform composition. Other considerations enter but need not be considered here.

Primordial differentiation, which would be expected to proceed more or less uniformly around the earth, seems to offer greater possibilities for diversification of earth materials leading to compositional

[4] L. H. Adams, "Temperatures at Moderate Depths within the Earth," *Jour. Wash. Acad. Sci.*, Vol. XIV (1924), pp. 459–72.

zoning and to segregation of metals than does occasional differentiation during geologic time from a succession of locally created magma bodies. Moreover, there is some doubt as to whether conditions surrounding such a created magma chamber offer promising facilities for differentiation.[5] It is more than possible that secondary magmas are active aggressive bodies which tend to assimilate rather than differentiate, and would, therefore, not permit the delicate processes needed for metal concentration.

The hypothesis of primordial differentiation to explain mass diversification of igneous rock is accordingly expanded in an attempt to account for metal segregation. If metals result ultimately from the differentiation of earth material, it would seem obvious that the time of their segregation would most likely coincide with the processes which produced concentric compositional zoning; that is, in the period of universal differentiation at the birth or solidification of the earth. The more positive the evidence becomes that the earth suffered primordial and delicate compositional zoning, the more reasonable the expectation seems that metals were primordially differentiated. It is expected from the associations of certain metals with characteristic rock material, as viewed at the surface, that each compositional zone in the earth would have segregations of corresponding metal associates. Segregations of typical nickel-ore minerals are expected to exist in the primordial shell of gabbro composition, those of chromite with peridotite, etc.

When a layer of magma is generated in the solid earth during geologic time, it may or may not be involved with the primordial concentration of metal that lies near its own horizon. In this concept the writer sees a possible explanation of the fortuity of association of metal and rock. It might be anticipated that some granites have tin and others none, that only an occasional diabase might become involved with the primordial segregation of silver, cobalt, etc., and that a few but not all gabbro bodies have associated nickel.

The hypothesis further implies that in geologic processes igneous materials tend to mix rather than unmix, and that unmixed magmas of differing compositions, and likewise magma and ore material, can

[5] De Lury, "Origin and Movements of Magma in a Strong Earth," *Amer. Jour. Sci.*, Vol. XXXIV (1937), pp. 222–34.

coexist and migrate to some extent without complete mixing. The possibility of local differentiation is not denied, but it may be that in the igneous processes metals may be dissipated rather than concentrated in many instances. Parental magmas may be heterogeneous and yield correspondingly diverse products, and ore materials, in particular those with heavy sulphide concentrations, may have less tendency to mix during migration than do diverse silicate magmas. According to this concept, workable deposits of metals occur because of the ability of ore magmas to migrate along with intrusions of rock magma without complete mixing. The existence of gradational types between rock and ore has usually been taken to indicate stages in differentiation. Is it possible that in many of these instances the gradation results from a mixing process? There is little doubt that some ore bodies intruded as magmas and were fundamentally not different from rock intrusives.

SUMMARY AND CONCLUSIONS

When the theory of magmatic differentiation is expanded to include the concept that all compositional diversification of igneous rocks belonging to at least the later eras of geologic time has arisen from a splitting-up of portions of a basaltic or more basic shell, considerable degree of uniformity is expected in the products of successive differentiations. There is sufficient absence of uniformity, in the writer's opinion, to permit a serious questioning of the value of the hypothesis. Similarly, if it is assumed that metals are differentiated in the same processes, the anticipated effects are not realized in a great many instances, as shown by the abundant evidences of fortuity of association of rock and ore, and by the general unevenness of geographic distribution of metals. The hypothesis of primordial differentiation of earth materials and consequent segregation of metals seems to eliminate many of the objections. In the latter concept primordial differentiation is followed in successive geological periods by local fusions of previously differentiated material. In these subsequent processes mixing is more important than differentiation in effecting serial diversity of igneous products. Primordial concentrations of metal are involved only occasionally with subsequent magmas and may be mixed with these or may accompany them with only partial mixing. Minor differentiation may

affect these subsequent magmas and supply evidences which may be wrongly interpreted as meaning that local differentiation is the major process in the formation of ore bodies.

With the appearance of the disturbing conclusions of Holmes,[6] derived from atomic weights of ore lead and rock lead, the present writer ventures to extend the hypothesis of primordial differentiation to include metalliferous deposits as well as rocks. If metals were concentrated in the main as primordial segregations, and these were tapped by subsequent magmas and redeposited in connection with later igneous processes, it is obvious that ore lead in each instance would be primordially differentiated and would have the same atomic weight in ores of all ages. The evidence of lack of contamination by rock lead seems to be opposed to the current theory of post-primordial concentration of metals.

To make the disturbing evidence from the atomic weights of lead agree with the extrapolated theory of differentiation, Knopf[7] suggested that a view favored by Bowen is supported, namely, that the universal magma during later geologic eras was a differentiate formed from peridotite by selective fusion. In this view all lead ores, irrespective of age, were derived from a primordial differentiate which might not have sufficient radioactive content to give rise to notable contamination of ore lead by so-called rock lead. This interpretation may be regarded as meeting the difficulty raised by lead atomic weights, but the theory of differentiation still faces objections raised by the evidences of fortuity in the distribution of metals.

It would be of interest to go farther and test the evidences of metal distribution and association on the assumption that the earth was built by planetesimal accretion and never was entirely molten. The compositional heterogeneity of such an earth might well account for the uneven distribution of metals and the fortuity of association of rock and ore. Furthermore, unless an undue amount of magmatic differentiation is postulated for ore concentration, the evidence of lead atomic weights need not be anomalous under the planetesimal hypothesis.

[6] *Loc. cit.*

[7] Adolph Knopf, "The Origin of Primary Lead Ores," *Econ. Geol.*, Vol. XXXII (1937), pp. 1061–64, with reference.

THE RECESSION OF GLACIERS IN MOUNT RAINIER NATIONAL PARK, WASHINGTON

C. FRANK BROCKMAN
Mount Rainier National Park

FOREWORD

One of the most outstanding features of interest in Mount Rainier National Park is the extensive glacier system which lies, almost entirely, upon the broad flanks of Mount Rainier, the summit of which is 14,408 feet above sea-level. This glacier system, numbering 28 glaciers and aggregating approximately 40–45 square miles of ice, is recognized as the most extensive single peak glacier system in continental United States.[1]

Recession data taken annually over a period of years at the termini of six representative glaciers of varying type and size which are located on different sides of Mount Rainier are indicative of the relative rate of retreat of the entire glacier system here. At the present time the glaciers included in this study are retreating at an average rate of from 22.1 to 70.4 feet per year.[2]

HISTORY OF INVESTIGATIONS CONDUCTED ON THE GLACIERS OF MOUNT RAINIER

Previous to 1900 glacial investigation in this area was combined with general geological reconnaissance surveys on the part of the United States Geological Survey. Thus, the activities of S. F. Emmons and A. D. Wilson, of the Fortieth Parallel Corps, under Clarence King, was productive of a brief publication dealing in part with the glaciers of Mount Rainier.[3] Twenty-six years later, in 1896, another United States Geological Survey party, which included Bailey Willis, I. C. Russell, and George Otis Smith, made additional

[1] *Circular of General Information, Mount Rainier National Park* (U.S. National Park Service, 1937), p. 3.

[2] The recession of the Stevens Glacier is excluded, owing to insufficient data.

[3] S. F. Emmons, "On the Discovery of Actual Glaciers on the Mountains of the Pacific Slope," *Amer. Jour. Sci.*, Vol. I (3d ser., 1871), pp. 161–65.

geological investigations. While their work was largely concentrated on the north and northwest slopes of the mountain, they also crossed to the south side, via the summit, being the first party to accomplish this feat. As a result of this survey, I. C. Russell published a detailed account of the major glaciers of Mount Rainier in the *18th Annual Report of the United States Geological Survey*.[4] Russell was the first to call attention to the evidence of glacier recession here, and in his paper he states: "Every glacier about Mount Rainier that was examined by the writer furnished evidence of a recent recession of its terminus and a lowering of its surface. In two instances—the Carbon and the Willis[5] glaciers—rough measurements of the amount of these changes during the past fifteen years were obtained."[6]

The first study of glacier movement in Mount Rainier National Park was made in 1905 by Professor J. N. LeConte, of the University of California. Professor LeConte made a brief investigation of the flow of the Nisqually Glacier during July of that year.[7] Nothing further was undertaken along this line until 1930, when, through the co-operation of the city of Tacoma (Department of Public Utilities), the United States Geological Survey (Water Resources Division), the United States National Park Service, and the United States Bureau of Public Roads, a study of the lower Nisqually Glacier was instituted in an effort to determine the rate of flow in more recent years.[8]

In 1910, 1911, and 1913 the topographic map of Mount Rainier

[4] "The Glaciers of Mount Rainier," *18th Ann. Rept. U.S. Geol. Surv.*, Part II (1897), pp. 350–415.

[5] Now known as the North Mowich Glacier.

[6] No detailed recession data were given, however.

[7] "The Motion of the Nisqually Glacier, "*Sierra Club Bull.*, Vol. VI, No. 2 (1907), pp. 108–14. Professor LeConte's observations indicated that an average maximum daily movement of 16.2 inches occurred at a point 558 feet from the east edge of the glacier, and an average minimum daily movement of 6.1 inches occurred 75 feet from the west edge. The glacier was 1,483 feet wide where this study was made, and, while the elevation is not given, it may be assumed from the width of the glacier that it was at about the 5,000-foot level.

[8] Llewellyn Evans, "1931 Progress Report on Nisqually Glacier Study" (1932). (Results of this study were not published, but a typed manuscript is included in the park museum, Mount Rainier National Park, Longmire, Wash.) This report indicates that at an elevation of 5,400 feet the average maximum movement over a period of 246 days (Aug. 31, 1930—June 12, 1931, incl.) was 758.4 inches, or 3.08 inches per day.

National Park was prepared by the United States Geological Survey.[9] The very comprehensive understanding of the glacier system here, which such an undertaking naturally afforded, was productive of the detailed and excellent description of the glaciers of Mount Rainier by F. E. Matthes.[10]

The tabulation of annual recession records on the glaciers of Mount Rainier was first undertaken in 1918, when F. W. Schmoe, the first park naturalist of Mount Rainier National Park, and Professor Henry C. Landes, of the University of Washington, collaborated in the determination of several early locations of the terminus of the Nisqually Glacier by means of old photos and authentic historical records. They also marked the extremity of the ice in that year. Since that date annual data have been taken on the recession of the Nisqually Glacier, first by Schmoe and, since 1928, by the writer, who succeeded Mr. Schmoe in the capacity of park naturalist of this area.

In addition to recession studies made on the Nisqually Glacier, the writer also established markers at the termini of the Emmons Glacier (1930), Carbon Glacier (1930), South Tahoma Glacier (1931), Paradise Glacier (1932), and the Stevens Glacier (1934).[11]

GEOGRAPHIC LOCATION AND CLIMATIC FACTORS

Mount Rainier National Park lies west of the crest line of the Cascade Range, a portion of which forms a part of the eastern park boundary and which is a north-south climatic boundary in the state of Washington. The prevailing winds from the west are heavily laden with moisture from the Pacific Ocean. As these winds rise in passing over the Cascades, rapid condensation of this moisture takes place, which accounts for the heavy precipitation in this area. The existence of the large glacier system on Mount Rainier is, naturally, due to this heavy precipitation. Over 75 per cent of it occurs be-

[9] *Topographic Map of Mount Rainier National Park* (U.S. Geol. Surv., 1934).

[10] *Mount Rainier and Its Glaciers* (U.S. National Park Service, 1922).

[11] "Record of Glacier Recession Measurements Made in Mount Rainier National Park, September, 1937, together with a Summary of Data Previously Taken" (U.S. National Park Service, 1938; typed MS in the library of the park museum, Mount Rainier National Park, Longmire, Washington); C. Frank Brockman, "Glacier Recession in Mount Rainier National Park" (Mount Rainier National Park "Nature Notes," Vol. XV, No. 4 [1937]) (mimeographed bulletin).

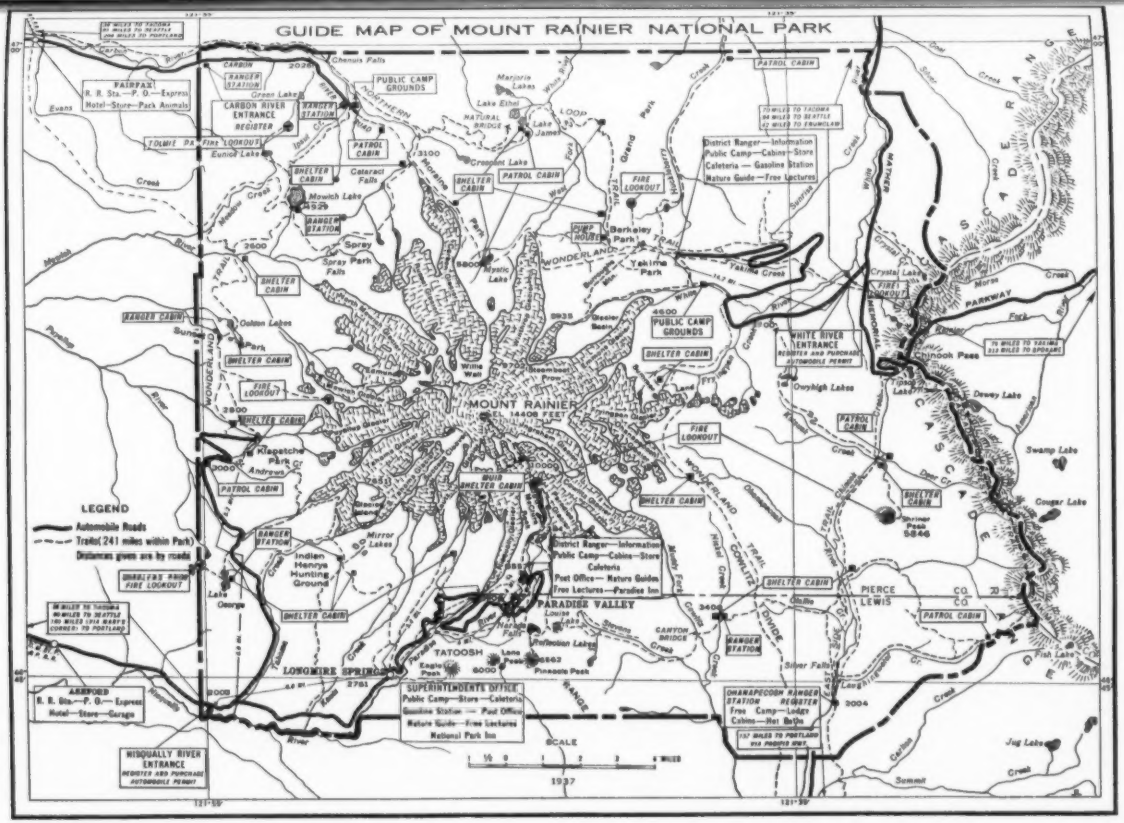

FIG. 1.—Guide map of Mount Rainier National Park (from the *Mount Rainier National Park Circular of General Information* [1937]). By permission of Dr. H. C. Bryant, assistant director, National Park Service, Washington, D.C.

tween October 1 and May 1, and a large portion of this moisture falls as snow.

Meteorological data are available for Longmire (2,760 ft.), Paradise Park (5,557 ft.), and the Carbon River entrance (1,716 ft.). The first two locations are on the south side of Mount Rainier National Park, while the latter is in the northwest corner of the area. However, owing to the very incomplete nature of the Carbon River records, these have not been included in the tabulations (Table 1).[12]

TABLE 1

Month	Average Monthly and Annual Precipitation		Average Monthly and Annual Snowfall		Average Monthly and Annual Temperature*		Highest Temperatures Recorded*		Lowest Temperatures Recorded*	
	Longmire	Paradise	Longmire	Paradise	Longmire	Paradise	Longmire	Paradise	Longmire	Paradise
January	12.57	15.93	44.6	110.8	30.3	26.3	58	62	− 9	−14
February	7.97	9.28	30.1	64.5	32.0	27.2	59	58	− 8	−12
March	8.06	10.67	33.8	96.7	35.2	27.9	73	66	9	0
April	5.07	6.31	13.8	51.7	40.9	34.2	85	70	12	2
May	4.01	4.97	2.5	23.3	47.7	40.8	95	88	21	14
June	2.73	3.59	0.0	6.3	54.7	46.1	98	86	28	13
July	1.12	1.28	0.0	0.4	59.8	51.6	105	86	33	20
August	1.73	2.97	0.0	Trace	60.6	50.7	99	100	35	24
September	3.79	7.18	Trace	7.5	52.5	44.9	95	83	24	18
October	7.89	9.79	1.1	21.4	46.4	40.6	88	79	17	2
November	10.19	11.58	15.2	64.8	37.8	33.6	76	69	8	2
December	13.05	15.41	28.8	101.6	31.6	27.4	60	60	− 7	−20
Annual	78.25	100.14	178.9	578.5	44.1	38.0	.....	.....	.....	.....
Length of record	1909–36	1918–36	1912–36	1920–36	1913–36	1921–36	1913–36	1921–36	1913–36	1921–36

* All temperatures are in Fahrenheit.

METHODS USED IN MEASURING THE RECESSION OF THE GLACIERS IN MOUNT RAINIER NATIONAL PARK

The determination of the actual end of the ice in the case of practically all the glaciers on Mount Rainier is a difficult matter. The inclination of the ice at the termini, the varying widths of the

[12] L. C. Fisher, *Climatic Summary of the United States*, Sec. I: *Western Washington* (U.S. Weather Bureau, 1936); *Climatological Data, Washington Section* (U.S. Weather Bureau, monthly climatological review, 1931–36, incl.).

termini, the presence of ice caves or ice "lips," the character and depth of the morainal material, the irregular shapes of the termini, and numerous other factors all contribute to the confusion in determining the actual end of the glaciers in question. The abundance of morainal material in the case of the Emmons Glacier and the South Tahoma Glacier made it particularly difficult to determine the exact extent of the ice in those instances.

Because of these confusing factors, the true terminus of each glacier measured has been considered as that point in the ice from which the main stream emerged.[13] This method, of course, causes some inconsistency in the data from year to year, as in the case of the Emmons Glacier, but it is felt that over a period of years the average annual recession figure for each glacier will be more nearly accurate than if miscellaneous or poorly defined points were selected.

The method by which recession is measured differs with the glacier in question. In the case of the Emmons Glacier measurements are made from points on a base line located by instrumental survey. Whenever possible, rocks which have the appearance of permanency are also marked, and check measurements are made from these. Large rocks below the Nisqually, South Tahoma, and Stevens glaciers are marked annually, and recession is tabulated from measurements made from these. In the case of the Carbon Glacier a large rock outcrop over 700 feet below the terminus was selected in 1932 after several unsuccessful attempts had been made to locate a permanent marker. In addition, a rock on the moraine below the ice face was marked in 1936 for use in future check data. Three points along the broad front of the Paradise Glacier have been marked, and measurements have been made from these each year.

NISQUALLY GLACIER

Recession data have been taken annually on the Nisqually Glacier since 1918, and, in addition, the position of its terminus has been located by authentic historical records and old photos for three periods previous to 1918, one as far back as 1857.[14]

[13] The Paradise Glacier, because of individual conditions, is an exception to this rule.

[14] In July, 1857, Lieutenant A. V. Kautz, U.S.A., with several companions made the first known attempt to ascend Mount Rainier. This party approached their objective

Table 2 indicates that the rate of recession in the case of the Nisqually Glacier has been much greater since 1918 than was the

FIG. 2.—Terminus of the Nisqually Glacier in 1937, as viewed from the bridge which spans the Nisqually River; the approximate location of the terminus of the Nisqually Glacier in 1885.

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from Fort Steilacoom on Puget Sound by way of the Nisqually River valley. At its upper end they encountered a wall of ice which was the terminus of the glacier. In his diary of the trip Kautz states: ". . . . Where the glacier terminated, the immense vein of granite that was visible on both sides seemed to form a narrow throat to the great ravine, which is much wider both above and below" (E. S. Meany, *Mount Rainier—a Record of Exploration* [New York: Macmillan Co., 1916], pp. 72–93).

When annual recession measurements were initiated in 1918, this place was identified 760 feet below the present bridge which spans the Nisqually River.

According to Len Longmire, grandson of James Longmire who established a mineral claim about the springs near the present park headquarters and village of Longmire in 1883, the glacier terminated in 1885 at a point about where the present bridge crosses the river. He states, further, that the terminus occupied a position about 140 feet above this site in 1892 and that members of the Longmire family were the first to notice that this glacier was receding. Accustomed to obtaining ice from the terminus of the glacier for the purpose of preserving perishable foods, they observed that it was necessary each year to make longer trips in order to obtain ice. In consequence, the position of the terminus became identified with near-by topographical features, making it possible, when recession measurements were begun in 1918, to identify the approximate position of the end of the Nisqually Glacier fairly accurately for 1885 and 1892.

case during any previous period of years for which recession records are available. This may be summarized as in Table 3.

EMMONS GLACIER

Recession measurements on the Emmons Glacier, largest on Mount Rainier, were initiated on September 22, 1930. A base line,

TABLE 2

TABULATION OF RECESSION DATA

Period	Feet	Period	Feet
1857–85	760	1926–27	43
1885–92	140	1927–28	89
1892–1918	1310	1928–29	52
1918–19	59	1929–30	118
1919–20	46	1930–31	49
1920–21	106	1931–32	50
1921–22	67	1932–33	44
1922–23	44	1933–34	155
1923–24	83	1934–35	54
1924–25	73	1935–36	65
1925–26	86	1936–37	55

TABLE 3

AVERAGE ANNUAL RATE OF RECESSION

Period	Feet
1857–1937	44.3
1857–85	27.1
1885–92	20.0
1892–1918	50.3
1918–37	70.4

bearing N.20° W., was surveyed from a point established on the south side of the White River. This line crossed the glacier above the place where the stream emerged from the ice, and thus, in accordance with the policy of considering the point on the ice from which the main stream emerged as the true terminus, the distance from the base line to the ice in 1930 was nil.

The use of a base line was deemed advisable in this case, for no rocks of sufficient size to insure stability were to be found in the

river bed below the ice.[15] The terminus presented the appearance of a wide, irregular, concave curve with a broad lobe of moraine-covered ice extending downstream on each side of the White River, which emerged from the ice near the middle of this curve. It was thus apparent that it would be difficult to compute the recession with any degree of accuracy other than by means of measurements from a base line.

FIG. 3.—Terminus of the Emmons Glacier in 1937, as viewed from a point on the trail overlooking the ice.

In the fall of 1931 it was obvious that the recession for the year 1930–31, as well as the year following, would have little significance if considered individually. At this time the ice face presented a very uneven apparance. A deep and very narrow cleft had formed in the vicinity of the stream, with lobes of ice extending downstream on both sides of the White River almost to the base line.

[15] In later years when such rocks presented themselves, they were marked so that check data could be taken from them. Few of the rocks so marked were able to resist the flood periods of the White River until 1936. Consequently, most of the recession data have been derived from measurements made from the ice face to points on the base line.

In the fall of 1932 the stream issued not from a point in the ice similar to its position of the previous year but from the side of the left lobe. In the fall of 1933 the course of the stream had changed again and was once more emerging from the ice at a point comparable to its position in 1932. The apparent "advance" of the glacier recorded for the year 1933–34 was, of course, due to the change in the position of the stream rather than the downward movement of the ice. Changes at the terminus have not been as

TABLE 4

TABULATION OF RECESSION DATA

Sept. 22, 1930	Base line surveyed from the permanent marker
1930–31	Recession of 142 feet (no supplementary measurement)
1931–32	Recession of 2.5 feet (on supplementary measurement a recession of 19 feet)
1932–33	Recession of 48.5 feet (on supplementary measurements a recession of 32 feet)
1933–34	"Advance" of 1.5 feet (due to the change in the position of the stream rather than any downward movement of the glaciers; on supplementary measurements a recession of 132 feet)
1934–35	Recession of 67 feet (on supplementary measurements a recession of 30 feet)
1935–36	Recession of 193 feet (on supplementary measurements a recession of 100 feet)
1936–37	Recession of 10 feet (on supplementary measurements a recession of 16 feet)

radical since 1934, but the examples noted will indicate why the use of a base line was necessary for accurate computations.

In addition to recording measurements from the base line to the point in the ice from which the stream emerged, supplementary data were also taken. These data were computed from measurements made from the base line, or rocks in some cases, to other points on the ice face (Table 4).

The recession of the Emmons Glacier since 1930 may be computed in four different ways from Table 4. On the basis of those recession figures, which consider the point on the ice face from which the stream emerges as the true terminus, the average annual recession is 65.9 feet. On the basis of the supplementary measure-

ments, the average annual recession is 54.8 feet. If the recession indicated by each method is averaged each year, and the average annual recession computed from these yearly average figures, the average annual recession is 54 feet. The average of the three results indicates an average annual recession of 58.2 feet.

CARBON GLACIER

The initial attempt to establish a permanent point from which to compute annual recession data on this glacier was made on Sep-

FIG. 4.—Terminus of the Carbon Glacier in 1937, as viewed from the marker from which recession is measured, 870 feet from the ice.

tember 22, 1930. This original marker, as was a second point established in the following fall, was lost.

The third attempt was made on October 1, 1932. A large rock outcrop on the southwest side of the Carbon River 723 feet from the terminus was selected and appropriately marked. This marker has persisted since that time, and the recession of the Carbon Glacier has been computed from that point annually. In addition, a second marker, known as point *X*, was established nearer the ice face on

September 18, 1936. Check data have been taken annually since that time. Table 5 indicates that the average annual recession of the Carbon Glacier since 1932 is 29.4 feet.

TABLE 5

TABULATION OF RECESSION DATA

Sept. 22, 1930	Original marker established
1930–31	Original marker not found; second marker established
1931–32	Second marker not found; third marker established
1932–33	Recession of 12 feet (marker 735 feet from the terminus)
1933–34	Recession of 29 feet (marker 764 feet from the terminus)
1934–35	Recession of 24 feet (marker 788 feet from the terminus)
1935–36	Recession of 62 feet (marker 850 feet from the terminus) Point *X* established 327 feet from the terminus for use in future check measurements
1936–37	Recession of 20 feet (marker 870 feet from the terminus) Point *X* 347 feet from the terminus

SOUTH TAHOMA GLACIER

Recession studies were initiated at the terminus of this glacier on October 1, 1931, when a large rock 140 feet from the terminus was marked.

The ice face in question is actually the combined mass of the lower part of the South Tahoma Glacier and an arm of the Tahoma Glacier, these two merging below Glacier Island (see map, Fig. 1). The former occupies the canyon to the southeast of Glacier Island, while the latter is found on the west side. Eventually these two bodies of ice will separate and retreat up their own specific canyons.

In the light of recent observations, the retreat of this combined ice face is not proceeding in an orderly and uniform manner. Owing to the irregular melting of the ice, it is unlikely that this retreat will bring about a clear-cut, simultaneous division of the two ice fields when the apex of Glacier Island is reached. Instead, factors which influence the melting of the ice may cause either the narrower South Tahoma Glacier or the more exposed arm of the Tahoma Glacier to be pinched off before that time. While this will undoubtedly complicate matters relative to the recession measurements in the future, the more consistent of the two ice streams, or both, will

be measured when a decision as to which glacier to follow has to be made.

On September 7, 1934, in anticipation of a change in the course of the stream which would cause it to emerge from a different point in the ice, a second marker was established. This marker, known as point *B*, was 142 feet from the ice. By 1935 the anticipated change in the stream had occurred, and the point from which the stream

FIG. 5.—Terminus of the South Tahoma Glacier in 1937, as viewed from the "established photo point" on the river bar.

emerged in former years was entirely covered with morainal debris which had lodged at the base of a high ice face which crowned that point. In the fall of 1936 and 1937 this ice face was smaller and the accumulation of debris larger. The stream has since continued to issue from the same point in the ice face as in 1935.

On September 25, 1936, a third marker was established below another ice face which had taken form some distance from points *A* and *B*. This marker was not found in the fall of 1937. However, a new marker, 77 feet from the ice, was established for future recession measurements at this place. Table 6 indicates that the

average annual recession of the South Tahoma Glacier is 50 feet from point *A*, and 30.6 feet from point *B*. Considering the point from which the stream emerges as the true terminus (in this case the tabulations from point *A* are selected for 1932, 1933, and 1934, while tabulations from point *B* are used for 1935, 1936, and 1937), the average annual recession is 35.8 feet. An average of the three results, noted above, indicates an average annual recession of 38.8 feet per year.

TABLE 6

TABULATION OF RECESSION DATA

Oct. 1, 1931	Original marker placed 140 feet from the terminus
1931–32	Recession of 37 feet (marker 177 feet from the terminus)
1932–33	Recession of 13 feet (marker 190 feet from the terminus)
1933–34	Recession of 73 feet (marker 263 feet from the terminus)
	Point *B* established 142 feet from the ice
1934–35	Point *A*—recession of 61 feet (marker 324 feet from the ice)
	Point *B*—recession of 42 feet (marker 184 feet from the terminus)
1935–36	Point *A*—recession of 66 feet (marker 390 feet from the ice)
	Point *B*—recession of 37 feet (marker 221 feet from the terminus)
	Point *C*—established 107 feet from the ice
1936–37	Point *A*—recession not computed; point on ice face too indefinite for accuracy
	Point *B*—recession of 13 feet (marker 234 feet from the terminus)
	Point *C*—marker established in 1936 not found; new point established 77 feet from the ice

PARADISE GLACIER

To augment recession studies made on the four active valley glaciers (Nisqually, Emmons, Carbon, and South Tahoma), similar measurements have been made at the termini of two intermediate glacierets, known as the Paradise and Stevens glaciers. The Paradise Glacier is the better known and more accessible of the two, and on September 23, 1932, three prominent rocks in front of its broad face were selected and appropriately marked as points *A*, *B*, and *C*. Measurements have been made annually, whenever possible, from each of these points to the nearest ice.

FIG. 6.—Paradise Glacier in 1937, as viewed from the "established photo point" on the ridge overlooking the ice. Points *A*, *B*, and *C* are located along the front of the glacier. The tongue of ice to the right is the Stevens Glacier.

Actually, the terms "Paradise Glacier" and "Stevens Glacier" are merely names given to lobes of a parent ice field. The lobe known as the Paradise Glacier originally extended down the extreme upper portion of the Paradise River Valley; that known as the Stevens Glacier extends down another valley and gives rise to Stevens Creek.

TABLE 7

TABULATION OF RECESSION DATA

Year	Point	Distance from the Marker to the Ice (in Feet)	Recession Noted (in Feet)
1932.....	*A*	13	Points established
	B	38	
	C	45	
1932–33.....	*A*	Covered with snow	Unknown
	B	43	5
	C	52	7
1933–34.....	*A*	20	7 (since 1932)
	B	78.5	35.5
	C	76	24
1934–35.....	*A*	Covered with snow	Unknown
	B	102	23.5
	C	Covered with snow	Unknown
1935–36.....	*A*	92	72 (since 1934)
	B	162	60
	C	110	34 (since 1934)
1936–37.....	*A*	Edge of ice covered with snow	Unknown
	B	190	28
	C	Edge of ice covered with snow	Unknown

In recent years the Paradise Glacier has receded to a point where it represents little more than a flank of the parent ice field. The amount of water which flows from it has been materially reduced, and the spectacular ice caves of a few years ago are no longer extant.

From Table 7 it is seen that the average annual recession of the Paradise Glacier is 19.7 feet from point *A*, 30.4 feet from point *B*, and 16.2 feet from point *C*. The average annual recession of the entire ice front, as computed from the averages of the three points noted, is 22.1 feet.

FIG. 7.—Terminus of the Stevens Glacier in 1937, as viewed from the point which marked the edge of the ice in 1935.

STEVENS GLACIER

Recession measurements on this glacier were initiated on September 5, 1934, when a point was established upon a prominent rock 52 feet from the end of the ice. In the fall of 1935 it was impossible to locate this original marker as it had in all probability been washed away sometime during the intervening period. A second point was established upon a solid, stationary rock face that was just emerging from the ice at the terminus.

TABLE 8

TABULATION OF RECESSION DATA

Sept., 1934	Original marker established
1934–35	Original marker not located; second point established
1935–36	Recession of 146 feet
1936–37	Recession of 187 feet

Recession data in the case of the Stevens Glacier are still scanty, for only two years have elapsed since the permanent marker was established. In addition, the extreme recession indicated by Table 8 is misleading, as the glacier terminates in a long tongue of ice that extends some distance from the main body. The very rapid melting of this ice tongue is, naturally, reflected in the recession data. Such an apparently excessive annual recession will be the rule for at least two more years when, following the disintegration of the ice tongue, a more normal retreat will become evident.

REVIEWS

Das Magma und seine Produkte, Teil I: *Physikalisch-chemische Grundlagen*. By PAUL NIGGLI. Leipzig: Akademische Verlagsgesellschaft, 1937. Pp. xi+379; figs. 276.

This volume is the first of two and, as its subtitle indicates, it deals with physical-chemical principles and data applicable to magmas; the second volume will deal with their application to the formation of rocks and mineral deposits. The author begins with a brief historical review of the investigations which have yielded present data upon magmatic components and gives a table of thermal constants of individual components, largely the melting-points of the nonvolatile constituents, and the melting-points, boiling- or sublimation-points and critical points of the more volatile constituents. In doing so he has here, as well as elsewhere in the volume, not always adhered to the one temperature scale. Thus we find the melting-point of anorthite given as 1,550° and again as 1,554°, and, in another table at the end of the book, summarizing the data of equilibrium in ternary systems, the melting-point of cristobalite is given as 1,713° and again as 1,728°. Since these discrepancies may be somewhat puzzling to the uninitiated, it is perhaps well to point out that the lower values refer to the gas-thermometer scale adopted by the Geophysical Laboratory, the higher values to the scale based on radiation thermometry. The differences are a matter of definition of the thermometer scale and do not represent discrepancies in the determinations by different investigators. Niggli has, indeed, omitted old values obtained by inadequate methods—a practice that might well be emulated by others in presenting tables of that kind. It is, however, somewhat surprising to find melting-points of sillimanite and ferrous metasilicate stated without comment, although these compounds suffer solid decomposition at temperatures far below that at which any melting occurs.

In the systematic treatment of his subject the author deals first with systems of nonvolatile components, illustrating the principles by theoretical diagrams and giving also the many actually determined diagrams, nearly all of which come from investigations carried out at the Geophysical Laboratory. The diagrams are of pleasingly uniform type, all well executed, clear, and incisive. In plotting some of the ternary dia-

grams he uses mol-per-cent diagrams of a special type, the molecular units chosen being such as to make the sum of the atoms Si, Al, Fe, Mg, Ca, Na, and K = 1 in each component. Thus the molecular unit of albite is $\frac{1}{10}$ $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ since the sum of Na, Al, and Si is 10. This is done in preparation for the detailed application of the diagrams to come in his second volume where it will enable him to get directly the *fm*, *al*, *c*, *alk* versus *si* ratios of his special type of rock-variation diagrams.

When discussing the various determined diagrams the author gives in full detail and with great clarity the manner in which these diagrams are used to deduce courses of crystallization. In systems with an incongruently melting compound or a series of solid solutions, he emphasizes the contrast between crystallization of the first kind and of the second kind. These correspond respectively with perfect equilibrium crystallization and fractional crystallization of the reviewer, who has stressed the importance of distinguishing them on account of their very different consequences.

Systems involving immiscible liquids are discussed, together with the examples which have been encountered in liquids rich in SiO_2. Here the author states that the system CaO-Al_2O_3-SiO_2 shows an equilibrium point of the type involving two crystal phases and two liquid phases, referring it to the theoretical type of his Figure 27, page 80. This is not correct. In the system under consideration two liquids are in equilibrium with only the one crystal phase, cristobalite.

After treating systems involving only nonvolatile constituents, the author then goes on to systems in which there is a great difference in the volatility of the components, one or more of them being easily volatile. In these types of systems there is only a limited number of determined diagrams. Most of the diagrams deal therefore with hypothetical examples. The theory of the subject is given in great detail both as it refers to distillation and boiling and also to the appearance of critical phenomena. The treatment is much like that in former publications by the author, and the principal outcome is his well-known classification of igneous phenomena into three temperature ranges.

1. Magmatic-melt range
2. Pegmatitic-pneumatolitic range involving critical phenomena and/or boiling
3. Hydrothermal-solution range

In a section dealing principally with reaction velocity the author briefly treats crystallization-differentiation of magmas and gives in diagrammatic form a relation between the principal phases of subalkaline

igneous rocks, which is substantially identical with that presented by the reviewer in his reaction series.

In summary, it may be said that the book is a worthy product of a master of his subject and is indispensable to every working petrologist.

NORMAN L. BOWEN

"The Pleistocene Geology of Nebraska," by A. L. LUGN, in *Nebraska Geological Survey Bulletin 10* (2d ser.). Lincoln, 1935. Pp. 223; pls. 2; figs. 38; tables 4.

This report embraces the fluvial and eolian deposits outside the glacial limits, as well as the glacial deposits and the fluvial and eolian deposits which are connected with them. The glacial deposits are restricted to the eastern end of the state within a distance of 75 to 100 miles of the Missouri River. They embrace only the two oldest drifts, Nebraskan and Kansan. The outlying fluvial deposits are found to correlate definitely with these two drifts, but the wind deposits are mainly of later age. The studies here reported have made clear the presence of Nebraskan drift in about as great extent as the Kansan and its extension a little beyond the Kansan limits in western Butler and Polk counties on the south side of Platte River valley. The name Nebraskan thus seems appropriate for this oldest sheet of drift. The presence of a Nebraskan gumbotil, together with a great amount of pre-Kansan erosion of the till, shows it to be much older than the Kansan drift.

The Nebraskan drift is best preserved in the deep preglacial valleys some of which extend to a level nearly 100 feet below the present streams. The deposits are revealed chiefly by well records, for there are very few exposures. These records show that it reaches a thickness of fully 100 feet as now preserved after considerable erosion. Lying as it does so largely below present stream-level, it is better preserved than the overlying Kansan drift, for that drift stands very largely above the main drainage lines. The Kansan has been reduced by erosion to a small percentage of its original bulk. The greater part of the Nebraskan drift, as now preserved, is an unoxidized and unleached blue till. The Kansan drift is oxidized nearly to its base and the surface portion is leached to a depth of several feet, even in places where a gumbotil has been developed on it. The leaching is more conspicuous there than on the valley slopes, for on them removal by erosion has kept fair pace with the leaching. The loess which

blankets these slopes often rests on unleached till, but on the uneroded upland it rests on gumbotil or a leached till of considerable depth.

A great accomplishment by Dr. Lugn has been the clear interpretation of the complex series of fluvial and eolian deposits outside the glacial limits and their relation to the two drift sheets. These deposits are mainly the product of streams that come from the Rocky Mountains or the bordering plains, and they have a descent with these streams to the vicinity of the glacial boundary. They are of such great thickness as to show that each of the glacial stages was of long duration. There are two sheets of sandy gravel, separated by weathered deposits of finer sand and silt. The lower, called the Holdredge formation, with a thickness of 50–100 feet in the vicinity of Platte River valley, is found to correlate with the Nebraskan drift. The overlying silt has a thickness of 20 feet or more. The upper gravel, called the Grand Island formation, is similar in thickness to the Holdredge and is the correlative of the Kansan drift. These formations are spread very widely in central Nebraska, covering the interval between the Platte and Republican rivers and extending some distance north from the Platte Valley. Dr. Lugn has been able to demonstrate through a series of carefully planned test borings that the underground drainage through these gravel formations passes southward from the Platte to the Republican Valley. He found that the level of the Platte River is at all times higher than the water-table level on the south side and that the stream has been eroding instead of aggrading its valley, in spite of its "braided" appearance, which other students have taken to be evidence of aggradation. It has carried away the upper part of the Grand Island formation, as well as the loess deposits of later age.

There are two loess deposits of widely different age, the earlier being the Loveland and the later the Peorian loess. The main part of the erosion of the Platte Valley within the glaciated part of Nebraska has been subsequent to the deposition of the Loveland loess. The valley is about 150 feet deep, and in places reaches a width of about 8 miles. It is thought by Dr. Lugn that there was very little valley development during the time the Kansan gumbotil was forming and that this was succeeded closely by the deposition of the Loveland loess. This being the case, its stratigraphic position seems likely to be in the late part of the Yarmouth interglacial stage. This will make it pre-Illinoian and a correlative of the pre-Illinoian loess found quite widely preserved in western and southern Illinois. This horizon for the Loveland was suggested by the reviewer in *Science*, May 24, 1929, in a dissent from an interpretation by G. F. Kay in the November 16, 1928, issue of the same journal that it is post-Illinoian in age. The

view held by Kay is presented by Dr. Lugn. In this he follows his old teacher, but in some other matters he seems to have shown more independence. Thus on page 152 he says:

> If the Iowan till area was topographically so situated that the Iowan till experienced vigorous erosion by wind and water, it seems reasonable to believe that it is just a remnant or residuum of its former self. Erosion under such conditions may be the best explanation for the absence of a gumbotil on the Iowan, for the absence of any great depth of leaching of the till and gravels, and for the absence of much of the till itself.

The Peorian loess occurs as an almost unbroken mantle over about 42,000 square miles of Nebraska, covering the glaciated part of the state and extending westward, giving place in western Nebraska to the sand hills. It was evidently brought in by winds blowing toward the east. It becomes finer in passing eastward, but maintains remarkable thickness all the way to the Missouri Valley and far eastward in Iowa. The Loveland loess has a redder color than the Peorian, which suggests derivation from the southwest.

FRANK LEVERETT

Outlines of Historical Geology. By CHARLES SCHUCHERT AND CARL O. DUNBAR. 3d ed. New York: John Wiley & Sons, 1937. Pp. 241; figs. 151; pls. 6. $2.50.

The third edition of this book bears little resemblance to the second, and for the most part it consists of a brief outline of the material presented by the same authors in their well-known larger textbook of historical geology, published in 1933. However, the organization has been greatly altered for the sake of brevity, and the systematic treatment of period after period has been avoided.

The first of the four parts into which the book is divided is a short discussion of the nature of the evidence from which the history of the earth is constructed, and it is written with obvious intent to interest as well as instruct the reader. The second part presents without technical verbiage the physical aspects of the subject, whereas the third, which is particularly well done, treats of the biologic record of the successive eras. The final portion of the book deals with the geologic history of mankind.

The book is frankly intended for a cultural course and not for the training of professional geologists, and it is written so that the student will not lose sight of the forest because of the trees. The authors have

accomplished their expressed objective, but of course their indulgence in extreme generalizations made it necessary to leave out many facts and details that would be desired by one person or another. Nevertheless, the book contains a concise account of all the essentials, and the authors and publishers may well be proud of it.

A. K. MILLER

The Maryland Geological Survey Reports, Vol. XIII. Edited by EDWARD B. MATTHEWS. Pp. 295; pls. 46; figs. 37. Baltimore: Johns Hopkins Press, 1937.

This volume deals principally with igneous and metamorphic terrains of the Piedmont belt but contains also some new data on the Upper Cretaceous sediments of the Coastal Plain series. Work on the Piedmont complex has been carried on under the supervision of Dr. Ernst Cloos. In a preliminary section Dr. Cloos describes the rigorous field and laboratory techniques which his assistants have employed in the preparation of their reports.

H. Garland Hershey has restudied the Port Deposit granodiorite complex, which underlies an area of 9 by 30 miles near the head of Chesapeake Bay. He finds it to be composed of three large and several small intrusive masses separated by schist and presents a new geologic map showing these relationships. Injection is believed to have been more or less continuous and progressively less basic in the later stages. Structural relationships, megascopic and microscopic, point to an age later than the Conestoga limestone of Pennsylvania, which is Ordovician. It is suggested that the Port Deposit intrusives were emplaced concordantly in a synclinal trough of the Wissahickon schist.

Carl H. Broedel presents the results of new investigations on six large domal structures affecting the Glenarm series north and west of Baltimore. They are believed to be the result of a complex and long-continued series of stresses involving vertical uplift as well as folding. The general alinement with Appalachian trends is interrupted by many irregularly disposed cross-structures reflecting pre-existing folds of the basement complex. The flanks of the domes may be overturned on either side of the principal axes. A relatively late set of transverse structures is recognized in flank areas underlain by the upper members of the Glenarm. It is believed that these have resulted from superficial compressive forces which were not transmitted below the relatively plastic Cockeysville marble near the base of the series.

John Marshall offers a brief contribution on the relations of an elongate mass of contorted volcanics lying within the area of the Port Deposit granodiorite. He has been able to distinguish a series of sediments interbedded with the flows, which he regards as Glenarm in age. This series was apparently compressed into isoclinal folds and intruded by gabbro before the emplacement of the granodiorite. Subsequent erosion has left the bedded series as the keel of a syncline entirely surrounded by the Port Deposit complex.

The results of new studies on the gabbro complex west of Baltimore are presented by Charles J. Cohen, with supplementary notes by Dr. Cloos. The gabbro is found to be a basin-shaped mass concordantly injected between layers of the Wissahickon schist and ringed around by the gneiss domes discussed by Broedel. Secondary features reflect the renewal of movement along complex pre-existing structures in the basement rock.

Certain new data on the Upper Cretaceous series of the Coastal Plain have been made available by fresh cuttings along the Chesapeake and Delaware Canal. These are presented by Charles W. Carter. Measured sections, fossil lists, and sedimentological descriptions constitute the body of his report. For the first time it has been found possible to extend certain New Jersey subdivisions of the Matawan and Monmouth groups into the state of Maryland.

WILLIAM F. READ

Essentials of Engineering Astronomy. By J. H. SERVICE. New York: Prentice Hall, 1937. Pp. xv+167; figs. 33. $2.50.

As the Preface states, the book is written for the engineer or geologist equipped with an engineer's transit and a good watch. It is clearly written, well illustrated (more than sixty pages are devoted to diagrams, etc.), and adequately serves its purpose.

A good, short, worth-while introduction to theoretical astronomy comprises the first chapter. The fundamental formulas of spherical trigonometry are stated without demonstration and all formulas necessary to the reduction of observations (the astronomical triangle in terms of azimuth, hour angle, latitude, and longitude) are derived as desired.

Part I is devoted to the Introduction, a brief summary of spherical trigonometry, the celestial sphere, time, corrections to observed altitudes, and problems in engineering astronomy. Problems of time and longitude are solved only by the use of figures, some of which are poorly chosen.

Part II comprises star identification, methods of determining azimuth, altitude and longitude, the striding level, the solar attachment, the sextant, and the computing machine. Twenty-six pages of this part are taken up with sample observation-data sheets.

H. W. STRALEY, III

The Cycle of Weathering. By B. B. POLYNOV. London: T. Murby & Co., 1937. Pp. xii+220; figs. 4. 10*s.* 6*d.*

Discussions of rock weathering are scattered through a wide literature, and in this volume the author has not only compiled the important data of the science but also contributed many of the results of his own researches, especially in connection with a philosophy of the weathering process. The book is organized in terms of the cycles through which the various elements pass in the earth's crust. After an introductory chapter on the concepts of the earth's crust and the crust of weathering, the author considers in turn the oxygen, carbon, nitrogen, silicon, aluminum, and iron cycles, as well as others, including chlorine, sulphur, and phosphorus. In each the treatment includes juvenile forms of the elements and the several transformations through which they pass. The treatment is largely geochemical, but ample space is devoted to the biological agencies which play a role.

The last section of the volume presents a philosophic system of general cycles of weathering, which Polynov divides into three types. The first cycle, attacking the primary minerals of the igneous rocks, yields orthoeluvium. A second cycle, involving the weathering of the deposits from the first cycle, yields paraeluvium. Finally, a third cycle, operating on recent drifts, may yield neoeluvium. Each of the cycles has its sequences of events and products, and the continuous operation of the cycles determines the general outline of the distribution of the products of weathering. Complexities may enter, however; vegetation may hinder the migration of the mobile products of weathering. The vegetation utilizes these mobile products, and in turn the composition of the upper surface of the weathered zone is modified by accumulations of humus. Thus Polynov's concepts are closely linked to the study of soils.

The book is well suited as an introduction to the large field of rock weathering, and the cyclical concepts introduced aid considerably in unifying the subject. The only disadvantage which impressed the reviewer was the general absence of figures or diagrams to represent the several cycles. The use of the book as collateral reading for physical geology

would be improved by the inclusion of such material. This disadvantage is less real than apparent, however, inasmuch as the material is ably presented, and the processes outlined may be comparatively readily visualized.

W. C. KRUMBEIN

The Colorado Delta. By GODFREY SYKES. (American Geographical Society Special Pub. 19 and Carnegie Institution of Washington Pub. 460.) Washington, 1937. Pp. 193; figs. 74; pl. 1. $4.00.

The Colorado Delta, which here, for the first time, receives monographic treatment, has developed under a unique combination of circumstances. Excessive variations, both seasonal and annual, affect the volume of discharge; the area available for deposition is limited to well-defined structural troughs; a zone of active crustal instability is included within the delta; and, finally, the portion fronting the Gulf of California is subject to tidal fluctuations on an unusual scale.

The principal sources of Mr. Sykes's information are three: first, personal observations accumulated during forty-five years of actual residence on or near the delta (1891–1935); second, the available records of early explorers, travelers, and settlers as far back as the sixteenth century, including the records of steamship navigation on the lower river from 1852 to 1876; and, third, the more systematic and detailed studies resulting principally from recent development of the delta lands through irrigation. The physiographic history of the delta recorded in these sources is reviewed in some detail; little attention is given to the problem of its development in prehistoric geologic time.

An attempt to formulate a co-ordinated concept of the delta as the product of erosional, transportational, and depositional functions performed by the Colorado River is based partly on the history of the delta and partly on recent observations, quantitative as well as qualitative, on the volume of discharge, load, character of transported material, etc. Various controlling factors, such as climate and vegetation, are considered.

A specially compiled topographic map (scale: ten miles to the inch), together with aerial and other photographs, illustrates the text. The classified Bibliography includes more than one hundred and fifty titles dealing with many phases of delta development, as well as special features of the area in question.

WILLIAM F. READ

Our Wandering Continents. By ALEXANDER L. DU TOIT. Edinburgh: Oliver & Boyd, Ltd., 1937. Pp. 366; figs. 48. 18*s* net.

The general tectonics of the globe is, in the very nature of the case, a theme of great complexity, which must be treated in the light of all available evidence arising from many different bits of earth behavior throughout recorded geologic history. It will be readily admitted that the true explanation of earth dynamics is to be obtained only by correct interpretation and proper evaluation of the very many processes, factors, and phenomena which are involved and which are to be brought into harmony. Basing much on certain processes and principles and giving little attention to other factors and other lines of evidence, in different proportions and combinations, has led to quite diverse concepts of the deformative evolution of the earth. One of the more spectacular of these is that of wandering continents, which is deployed and championed by Du Toit in this new book.

The author of this interesting and attractive volume has elaborated the hypothesis of continental drift in much detail by presenting an impressive array of geological observations which seem to him in accord with this hypothesis and to be better explained by it than by any other hypothesis. The pertinent observations and facts have been gathered by a painstaking study of the geology of the whole globe in its many aspects. Historical, stratigraphic, biologic, climatic, tectonic, and geophysical evidence has all been brought to bear on the problem. In fact, the focusing of so many different lines of evidence upon the main questions in hand may well be regarded as the chief contribution of this new study. Irrespective of the conclusions expressed, the assembled information itself and the skilful handling of it make the volume worthy of careful reading by any student of larger earth problems.

Certain advantages of the hypothesis are at once apparent. If a land mass can be drifted for a desired distance and can, in addition to drifting, be rotated either clockwise or counterclockwise at the wish of the manipulator, the possibilities of producing a given fit, pattern, or arrangement with other similarly movable land masses must be very considerable. Such maneuvering has few restrictions. But is it necessary? The reviewer is not convinced that broadly corresponding stratigraphic successions in two separate regions, more or less contemporaneous lava outpourings on a large scale, comparable glacial deposits, or related faunas necessarily indicate the close proximity of the areas which the author assumes to be required for their more or less parallel development.

The text is well written, lucid, and clear. The author's conviction that

the displacement hypothesis is far superior to any alternative current hypothesis is strongly expressed. As a manifestation of the writer's enthusiasm, some readers will doubtless note how often works cited for interpretations or conclusions in harmony with the continental-drift hypothesis are characterized as "brilliant," "illuminating," or "able," whereas some of those opposed suffer considerably in contrast. But any derogatory implications must be taken in good spirit by opponents as return compliments for their own severe criticism of the hypothesis of drifting continents. Dr. du Toit's new book is a stimulating contribution, whether one accepts his conclusions or not.

R. T. C.

The Physical Basis of Geography. By S. W. WOOLDRIDGE and R. S. MORGAN. London: Longmans Green & Co., 1937. Pp. xxi+445; figs. 272. $4.80.

The authors of this book contend that geomorphology should rightfully underlie the training of geographers, and on that basis they have written a book which would serve equally satisfactorily as a geology text, especially for courses which emphasize the erosion cycle as a framework. The first third of the book is devoted to aspects of diastrophism and volcanism as they affect land forms. There are chapters on the earth's interior, the major relief features of the earth, mountain-building, tensional forces in the earth's crust, vulcanicity and earth movements, and a short chapter on the nature of rocks. The authors present contemporary theories of diastrophism, inclining toward continental drift and subcrustal melting.

The remaining two-thirds of the volume discuss the several geological agents in terms of their influence on land forms. Throughout, emphasis is on Davis' cycle of erosion. Principles of stream-carved landscapes are developed in detail, and cycles of shore erosion, glacial erosion, and the like are discussed under appropriate heads. In many respects the approach is analytical, with an emphasis on underlying principles. Such an approach seems more fruitful than a purely descriptive treatment. The text is adequately illustrated with block diagrams and other figures.

W. C. KRUMBEIN

Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1935–1936. By ELDRIDGE C. JACOBS. Burlington: Free Press Printing Co., 1937. Pp. 155; figs. 9.

This report gives a good, simple description and discussion of the main features of the geology of Vermont, together with its mineral resources and mineral industries.

R. T. C.